ARL-SR-0357 ● JULY 2016

US Army Research Laboratory

Advances in Additive Manufacturing

Compiled by Marc S Pepi

A Compilation of Presentations by Marc Pepi, Todd Palmer, Jennifer Sietins, Jonathan Miller, Dan Berrigan, and Ricardo Rodriquez

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14. ABSTRACT

This special report is a compilation of the presentations provided at the 2016 Society for Machinery Failure Prevention Technology conference in Dayton, OH, on 23–26 May 2016. These 6 briefs were presented in the Additive Manufacturing session and provide a summary of work being performed in additive manufacturing by the Army, Air Force, and academia (Penn State University).

15. SUBJECT TERMS

3-D printing, validation and verification, nondestructive inspection, print-on-the-move, prototyping

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1. Introduction

The Society of Machinery Failure Prevention Technology (MFPT) held its first session in additive manufacturing (AM) at the 2016 conference in Dayton, Ohio, on May 24th, 2016. The presentations included work being performed within the Department of Defense (Army Research Laboratory [ARL] and Air Force Research Laboratory [AFRL]) as well as academia (Penn State University's Applied Research Laboratory) in the area of AM, with a focus on the technologies that the MFPT community could provide assistance with in this area (nondestructive testing and inspection, prognostics, diagnostics, structural health monitoring, failure analysis, data management, and sensors). This report includes all 6 of the presentations briefed at the conference.

Additive manufacturing is an emerging and disruptive technology that is transforming the manufacturing industry by allowing the designer to convert a computer model to a finished product in a few steps while overcoming the constraints associated with traditional manufacturing. There are many different technologies that comprise additive manufacturing, with the ability of utilizing polymer materials, metals, ceramics, fibers, and combinations therein.

Marc Pepi (Team Leader, Near-Net Shape Processing Team, ARL) briefed the status of an ARL program titled "On-Demand Manufacturing of Recycled, Reclaimed and Indigenous Materials". Mr Pepi indicated that AM on the battlefield could provide a logistical and tactical advantage for the Warfighter. This research focuses on 3 different aspects of additive manufacturing on the battlefield: 1) researching the formation of AM-grade metal powder from battlefield scrap and operating base waste, 2) potential of 3-D printing with sand to make casting molds for traditional casting processes on the battlefield, and 3) the use of recycled polymeric materials as feedstock for 3-D printers already on the battlefield within the Army Rapid Equipping Force Expeditionary Laboratory. Todd Palmer (Senior Research Associate and Associate Professor, Pennsylvania State University, Applied Research Laboratory) subsequently briefed his presentation "Role of Processing-Structure-Property Relationships in Developing Certification Protocols for Ti-6Al-4V Components", stressing that AM certification requires an understanding of the processing-structure-property relationships of the materials used for AM. He showed the importance of locking down the manufacturing process steps for repeatability in structure and properties of Ti-6Al-4V. Jennifer Sietins (Materials Engineer, ARL) then briefed "Additive Manufacturing Characterization Utilizing X-ray Computed Tomography", which showed the impact of X-ray computed tomography (CT) in the nondestructive inspection of

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AM parts for quality control, dimensional tolerance, and microstructural characterization.

The second AM session at the conference commenced with Jonathan Miller (AM Lead for Materials and Manufacturing Directorate, AFRL) presenting “Quality Assurance Methods for Additive Manufacturing Processes: Motivation, Challenges and Opportunities”, summarizing the importance of understanding the many implicit details of AM processing that affect the final structure and properties of the built component. Dan Berrigan (Program Manager and Research Scientist, AFRL) followed with a presentation titled “Air Force Vision and Challenges for Additive Manufacturing of Functional and Soft Matter Materials”, focusing on flexible hybrid electronics. He highlighted a few projects in additively manufactured electronics (e.g., batteries, capacitors, antennas) that span bench-level research to engineered solutions. In addition, he discussed the path forward as AFRL begins to explore the fundamental materials and processing challenges associated with pattern stimuli responsive materials and design of soft mechanical structures/actuators. The final paper was presented by Ricardo Rodriguez (Materials Engineer, ARL), entitled “ARL’s Additive Manufacturing for the Future Expeditionary Force”. This brief summarized the impact AM will have as the Army changes its focus from a traditional force into a more expeditionary force and hybrid AM techniques developed at ARL.

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2. Agile Additive Manufacturing in Austere Environments

Marc Pepi
(Army Research Laboratory, Weapons and Materials Research Directorate)

Additive manufacturing provides many cost-saving advantages to industry and the ability to manufacture complex and unique designs and geometries in a timely fashion. It also provides a more environmentally friendly means of production (leads to less waste than subtractive manufacturing). The Department of Defense is now interested in additive manufacturing as a means of being able to produce parts "on-demand" in extreme environments, such as on a ship or on a forward-operating base. However, there are technical challenges that need to be overcome to fully achieve this capability in the future. One such challenge is part quality, and the qualification and certification of parts produced in this manner to ensure the parts will not fail in service. This paper will discuss this and other challenges in more detail, and will provide a lead for other briefs on additive manufacturing to be featured in the same session.

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ARL

Agile Additive Manufacturing in Austere Environments

Marc Pepi, Nicole Zander, Jennifer Sietins, Ray Wildman, Margaret Gillan
US Army Research Laboratory
Aberdeen Proving Ground, MD

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Overview

ARL

- What is "Additive Manufacturing"?
- How can Additive Manufacturing help the DoD?
- Additive manufacturing on the battlefield…ARLs current work with:
  - ✓ Metal AM
  - ✓ Sand + Binder AM with traditional foundry methods
  - ✓ Polymeric 3D printing
- Conclusions

General Dwight D. Eisenhower noted, ***"You will not find it difficult to prove that battles, campaigns, and even wars have been won or lost primarily because of logistics."***

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What is Additive Manufacturing? ARL

Definition[1, 2]:

- **Additive manufacturing** is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.
- **3D printing** is the fabrication of objects through the deposition of a material using a print head, nozzle or other printer technology.

Eight processing steps common to additive manufacturing[3]:

- conceptualization and Computer-Aided Design (CAD)
- conversion to STereoLithography (STL) / Additive Manufacturing Format (AMF)
- transfer and manipulation of STL file on AM machine
- machine setup
- build product
- part removal and cleanup
- post-processing of part
- application of printed part

1 Additive Manufacturing Challenges and Opportunities for Military Applications, Joseph Hazeltine, RIAC TAT: RI-13-RMS#690/DO#290, November 2013.
2 ASTM-F2792-12a, "Standard Terminology for Additive Manufacturing Technologies", ASTM, West Conshohocken, PA, 2012.
3 Naval Postgraduate School Monterey, California Thesis, Additive Manufacturing In The Marine Corps, by Luke J. McLearen, June 2015.

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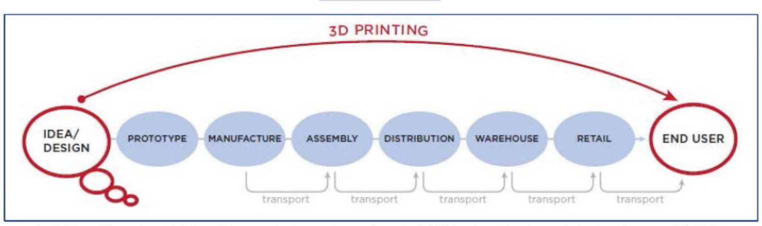
Additive Manufacturing Processes ARL

From: **"POTENTIAL OF ADDITIVE MANUFACTURING IN THE AFTER-SALES SERVICE SUPPLY CHAINS OF GROUND BASED MILITARY SYSTEMS",** BSc Graduation Assignment – Final report, Gino Balistreri, **University of Twente:** Department Industrial Engineering and Business Information Systems (IEBIS), Netherlands, 27 July 2015.

Vat Polymerization	Material Jetting	Material Extrusion	Powder Bed Fusion	Binder Jetting	Sheet Lamination	Directed Energy Deposition
• Stereo-lithography • Digital Light Processing	• Multi-jet Modeling	• Fused Deposition Modeling	• Electron Beam Melting • Selective Laser Sintering • Selective Heat Sintering • Direct Metal Laser Sintering	• Powder Bed and Inkjet Head Printing • Plaster-Based 3D Printing	• Laminated Object Mfg. • Ultrasonic Consolid-ation	• Laser Metal Deposition



Koff, W., and Gustafson, P., "3D printing and the future of manufacturing", CSC Leading Edge forum Technology Program, Fall 2012.

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U.S. ARMY RDECOM — Additive Manufacturing Impact on DoD — ARL

Key AM applications with high potential significance to DoD, now and in the future:

- Prototyping / Modeling
  - ➢ Intended to improve an existing design
- Tooling / Support Aids / Direct Part Production
  - ➢ Offers design flexibility, lighter weight, increased complexity, modularity, cost efficiency
- Maintenance and Repair
  - ➢ On-demand spare parts production, and field repairs (so far, better suited for depot level versus field-level)
- Medical
- Food

Even after a decade of combat operations in Iraq and Afghanistan, parts requisitioning was a long process. Every day a piece of equipment is inoperable because of a repair part is another day that a unit's overall capability is degraded.

*Additive Manufacturing Challenges and Opportunities for Military Applications, Joseph Hazeltine, RIAC TAT: RI-13-RMS#690/DO#290, November 2013.

*Naval Postgraduate School Monterey, California Thesis, Additive Manufacturing In The Marine Corps, by Luke J. McLearen, June 2015.

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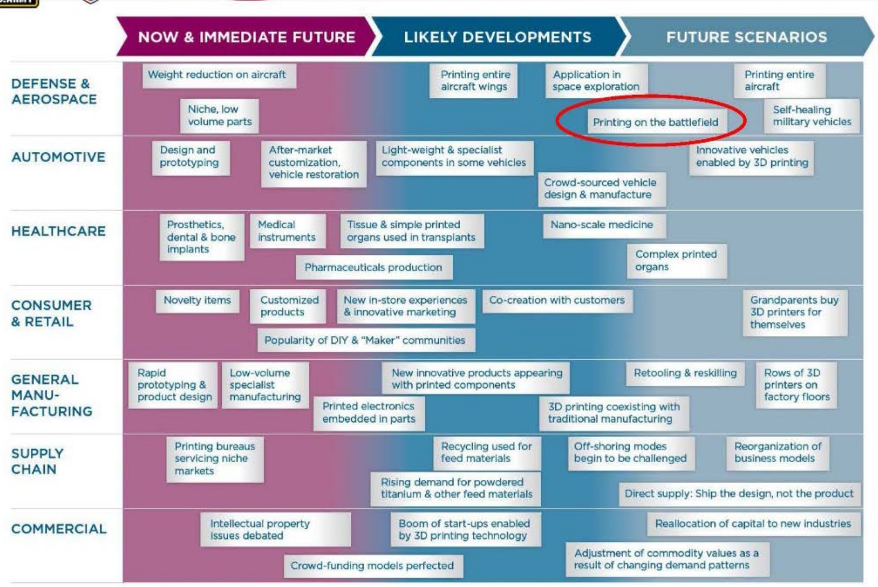

From: Koff, W., and Gustafson, P., "3D printing and the future of manufacturing", CSC Leading Edge forum Technology Program, Fall 2012.

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How can Additive Manufacturing Help the DoD?

Advanced Manufacturing Implementation Plan

CSA's Guiding Concept

39th Chief of Staff of the Army
Initial Message to the Army

We have the most skilled, ethical, and combat hardened Army in our Nation's history. No matter where we are around the world, America's Soldiers are displaying courage, commitment and character. We are demonstrating unparalleled competence and agility. And no matter the challenge, no matter how complex the environment, or how dangerous the situation, our Soldiers fight and win.

I am honored to lead this remarkable team.

I have three priorities:

#1. **Readiness:** (Current Fight) Our fundamental task is like no other – it is to win in the unforgiving crucible of ground combat. We must ensure the Army remains ready as the world's premier combat force. Readiness for ground combat is – and will remain – the U.S. Army's #1 priority. We will always be ready to fight today, and we will always prepare to fight tomorrow. Our most valued assets, indeed, the Nation's most valued assets, are our Soldiers and our solemn commitment must always be to never send them into harm's way untrained, poorly led, undermanned, or with less than the best equipment we can provide. Readiness is #1, and there is no other #1.

#2. **Future Army:** (Future Fight) We will do what it takes to build an agile, adaptive Army of the future. We need to listen and learn – first from the Army itself, from other services, from our interagency partners, but also from the private sector, and even from our critics. Developing a lethal, professional and technically competent force requires an openness to new ideas and new ways of doing things in an increasingly complex world. We will change and adapt.

#3. **Take Care of the Troops:** (Always) Every day we must keep foremost in our minds our Soldiers, Civilians, and their Families. Our collective strength depends on our people - their mental and physical resilience is at our core. We must always treat each other with respect and lead with integrity. Our Soldiers are the crown jewels of the Nation; we must love them, protect them, and always keep faith with them.

I am honored and proud to serve with you. Thank you for your service and commitment to a cause larger than yourselves.

Army Strong!

MARK A. MILLEY
General, United States Army
39th Chief of Staff of the Army

Foreword:
"The Army has been using AM for two decades to refurbish worn parts, create custom tools, and produce 3D visualizations for surgery rehearsals. We can aggressively exploit our manufacturing experience by placing 1) large scale systems in our depots and labs 2) medium scale systems at the Brigade level and 3) small mobile systems with our Brigade Combat Teams. World competitors are investing heavily in AM. Prudence demands the Army invest in this technology to shape an outcome suited for the Army of 2025 and Beyond".

Mary Miller Gustave F. Perna SES, Director of Technology Lieutenant General, GS, Office of the Assistant Secretary Deputy Chief of Staff, G-4 Research & Technology

…requires an openness to new ideas and new ways of doing things in an increasingly complex world. We will change and adapt.

From the US Army Advanced Implementation Plan, Volume I – MAR 2016.

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How can Additive Manufacturing Help the DoD?

According to General Dennis Via, Commander of Army Materiel Command, "printers could one day be embedded with squads, so that troops can manufacture weapons, tools or repair parts while they are in the field"

Logistical

Additive Manufacturing (AM), presents a significant opportunity for the U.S. Department of Defense (DoD) to enhance warfighter capability and reduce the current logistical footprint and total life cycle costs of numerous systems. AM offers the potential to reduce production time/costs for low-volume/high-value/complex-shaped components and the opportunity to manufacture in atypical, remote environments – such as forward operating bases (battlefield). AM may help DoD overcome a burdensome acquisition cycle requiring a great amount of cost, time, security, and storage space.

Tactical

With our enemies forced to innovate rapidly to survive, it's become increasingly important for the U.S. military to improve its own agility and flexibility. With additive manufacturing, parts could be produced where they're needed, when they're needed.

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Imagine a company or brigade able to produce repair parts on the battlefield. The Army alone spends billions of dollars buying parts every year. Every Army unit carries large parts stockpiles to keep rolling. This is costly and adds a huge burden to a unit as it deploys and in moving around the battlefield. A unit can't carry everything, and it's very difficult to predict what parts will be needed, so the Army uses various methodologies to figure out the most important ones on hand, balancing against cost and bulk. When a unit needs a part it doesn't have, equipment can sit for weeks until a replacement part is shipped all the way from a depot or the manufacturer. Worse yet, sometimes the part isn't available at all, triggering a potentially lengthy acquisition process. This problem has increasingly plagued the US military. Fewer manufacturers are interested in producing small batches of specialized military items for the fleets that have dwindled from their Cold War expanse. The explosion of unique, constantly evolving low-density equipment used in Iraq and Afghanistan has exacerbated this issue.

From:
*http://breakingdefense.com/2014/01/3d-printing-imagine-a-brigade-producing-parts-on-battlefield/

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U.S. ARMY RDECOM Additive Manufacturing on the Battlefield ARL

When dealing with safety concerns, it's also important to consider additive manufacturing as a supplier of temporary parts rather than final replacement parts. If a part breaks in the field, vital equipment may be down until the replacement part can be secured. This can sometimes require great time, great money, or both. But with additive manufacturing supplying a temporary part, equipment can remain operational until the actual replacement arrives. Because the temporary part is not intended to be the final replacement part, it doesn't need to meet the same stringent operating requirements. The additive manufactured part can bridge the gap, much like a spare tire on a car miles from an auto shop.

From: "Additive Manufacturing: Production on Demand", James Barkley, http://www.mitre.org/publications/project-stories/additive-manufacturing-production-on-demand, referenced 10/14/15.

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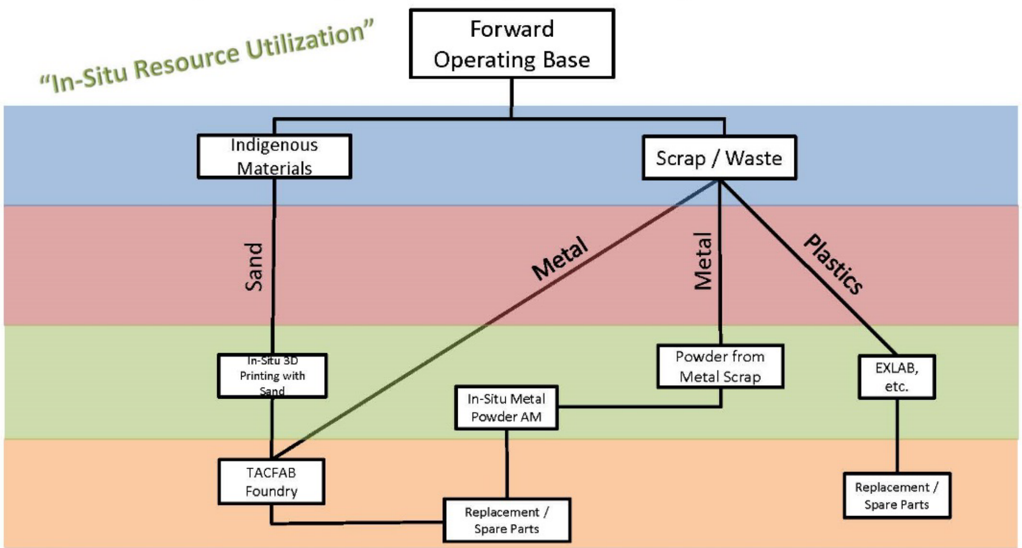
ARL is investigating how to bring AM capabilities to the battlefield:

1) Metal AM
   - Must overcome many challenges. Can we make powder in-theater from battlefield scrap, and FOB waste?
2) Sand/binder AM with traditional foundry capabilities
   - Can use recycled/reclaimed/scrap materials
3) Polymeric AM using recycled materials
   - Must overcome issue of dedicated OEM feedstock materials

- *Improved sustainment*
- *Maximized operational readiness*
- *Enhanced supply logistics*

Resource/Material/Process/Application Map for Battlefield AM



Source
Material
Process
Application

Goal: Utilize all available materials at FOBs to create useful structural components while reducing logistics tail, energy consumption, carbon footprint, and overall cost.

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- SBIR Phase I Topic A16-023, "Processing of Metallic Scrap Materials for Battlefield Additive Manufacturing" approved. Proposals received include the following technologies for AM Grade metallic powder production in-theater:
  - Melting + Lorenz Force Projection
  - Metal carbonyl process
  - Spark erosion
  - Atomization in mobile foundry
  - Rotating electrode wire/rod process -REP
  - Centrifugal Atomization or Plasma Rotating Electrode Process (REP)

Al 1100 – 97%
Al 6063– 95%
Al 6061 – 90%

- Received actual foreign metallic battlefield scrap from NGIC. Chemistry results based on hand-held LIBS analysis.

Cast Al 356 – 94%

4140 – 95%
Carbon steel – 94%
E52100 – 94%

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Metal AM on the Battlefield
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Typical waste on a Forward Operating Base:

This list is by no means exhaustive, but it was all present on the last FOB I operated from in RC-E this past fall.

1. MRE Trash: plastic bags of varying materials, cardboard boxes, cardboard food trays.
2. Clear plastic water bottles.
3. Cardboard boxes, cellophane and Styrofoam packing boxes from spare parts.
4. Used oil & air filters from vehicles and aircraft.
5. Used (waste) motor oil, used gear oil, used trans fluid and the 1qt - 55gal metal containers these fluids are shipped in.
6. Ammunition dunnage: This includes cardboard packing, wooden crates, wooden pallets, Styrofoam packing, individual metallic round shipping containers (for grenades & artillery rounds) empty brass cartridge casings ranging in size from 9 to 105mm, expended AT-4 tubes (I believe they're fiberglass or some type of composite) and metallic links.
7. Medical waste, human fecal waste.
8. Used batteries; mostly sizes AA (lithium), BA-5590 (lithium), and 24V automotive.
9. Used steel-belted off-road tires. If the FOB is utilized by an Armored Brigade, they will also have some used steel track on hand though not much.

The amounts of these waste materials present will vary with the pace of operations being conducted from that particular FOB as well. I hope this helps, but feel free to give me a call with any questions or if there's anything specific you're trying to determine if it's available or not.

v/r,
CPT, USA

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Challenges/gaps associated with metal powder additive manufacturing on the battlefield…

- Cost of equipment
- Footprint of equipment
- Weight of equipment
- Power needs
- Transport and storage of metal powders
- EDM equipment generally needed to remove parts from build plate
- Need for post-processing equipment
- Equipment supportability

…and what about…

- IP of parts being made in the field?
- Inspection / validation / verification?

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AM Grade metallic powder production on an operating base would reduce our logistics tail, and support operational readiness, by enabling component repair via gas dynamic cold spray or laser powder deposition technology.

http://www.boconline.co.uk/internet.lg.lg.gbr/en/images/20151005_95572_2333410_176194.jpg

http://www.vrcmetalsystems.com/images/VRC%20Gen%20III%20Cold%20Spray%20System.jpg

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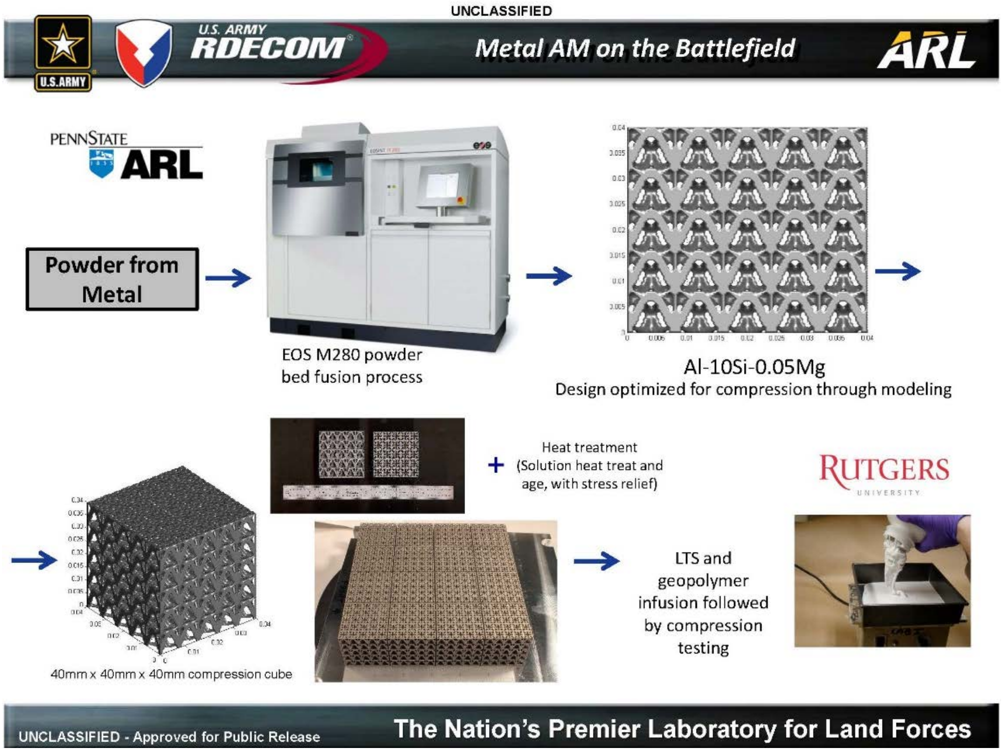

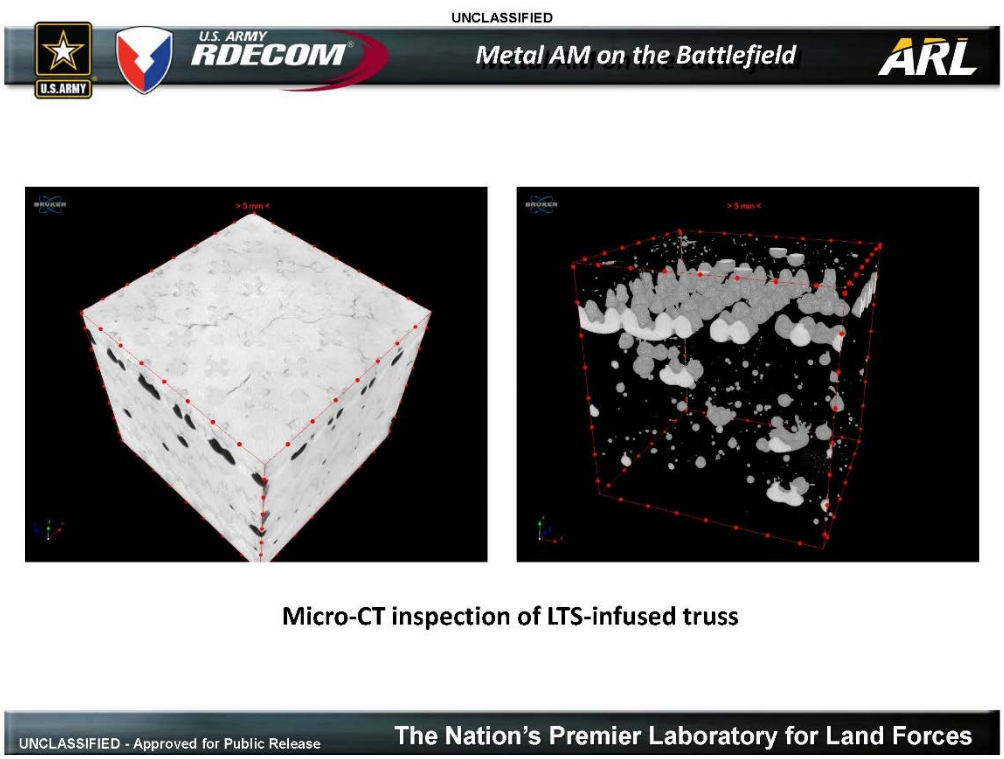

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Metal AM on the Battlefield

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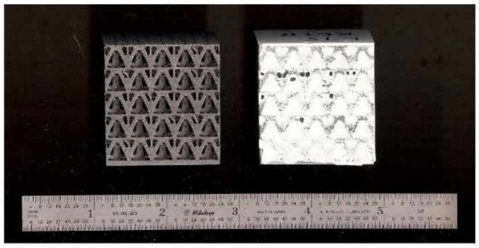

Aluminum truss made from EOS M280 powder bed fusion process (above, left), and similar truss infused with low-temperature solidified ceramic (above, right). Future protection of soft FOB shelters (right)?

From: http://battlerattle.marinecorpstimes.com/2014/05/12/on-the-ground-in-afghanistan-the-last-days-of-a-fob/

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Intermediary Step to Battlefield Metallic 3D Printing?

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In-Situ 3D Printing with Sand

"In-Theater 3D-printing with sand for the creation of casting molds"

•Objective: Increase in-theater manufacturing capability to perform repairs and make spare parts, reducing the logistics tail.

ExOne DIGITAL PART MATERIALIZATION

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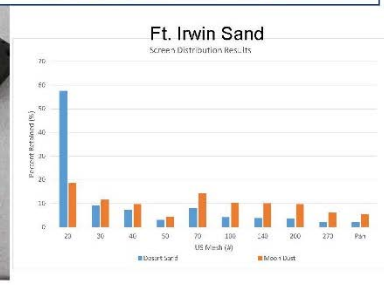
Intermediary Step to Battlefield Metallic 3D Printing?



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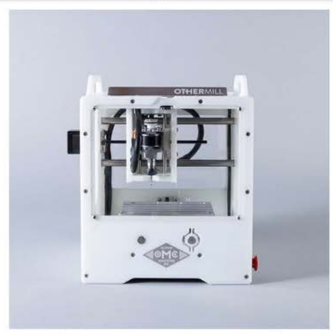
Intermediary Step to Battlefield Metallic 3D Printing?

- Alternative approach to metallic 3D printing, sand printing
- Othermill allows for precision 3D milling (positional accuracy to within 0.001 inch)
- Scrap metals (aluminum, brass, copper) will be cast into simple molds and milled to shape
- Limited to thin parts (<1.25 in)



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U.S. ARMY RDECOM — Metal AM on the Battlefield — ARL

Ground vehicle parts that might be technologically feasible through additive manufacturing:

Brake levers	Levers
Brake shoes	(Mirror) mounts
(Front axle) casings	Specific rings
Cross pieces	Steering wheels
Exhaust manifolds	Tow bars
Fan clutches	Universal joints
Flanges	Vent valves
(Metal/plastic) gaskets	Thrust collars
Guide carriages	Locking levers
Hoods	Filler necks

*From "POTENTIAL OF ADDITIVE MANUFACTURING IN THE AFTER-SALES SERVICE SUPPLY CHAINS OF GROUND BASED MILITARY SYSTEMS", BSc Graduation Assignment – Final report, Gino Balistreri, University of Twente: Department Industrial Engineering and Business Information Systems (IEBIS), Netherlands, 27 July 2015.

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U.S. ARMY RDECOM — Polymer AM on the Battlefield — ARL

Army Rapid Equipping Force (REF) Expeditionary Laboratory (ExLab III)

- Contains a polymeric fused deposition modeling (FDM) 3D printer; a Stratasys Fortus 250.

http://www.rapidreadytech.com/2012/08/u-s-army-brings-3d-printing-to-the-front-lines/

http://www.cadvision.fr/wp-content/uploads/Fortus-400mc-imprimante3D_part.jpg

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Polymer AM on the Battlefield
ARL
Problem: The Fortus 3D printers use only their proprietary filament feedstock
Question: Can we use waste polymers such as PET, PS, PP, LDPE/HDPE, PC as feedstock for 3D printing on FOBS?
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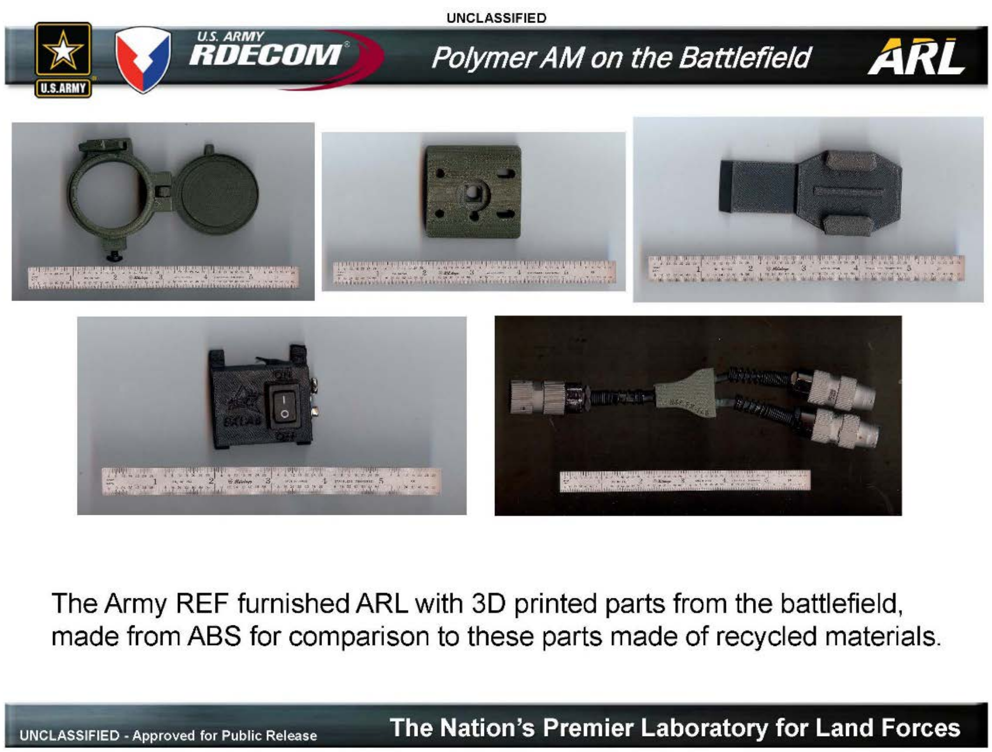
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Polymer AM on the Battlefield
ARL
The Army REF furnished ARL with 3D printed parts from the battlefield, made from ABS for comparison to these parts made of recycled materials.
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Polymer AM on the Battlefield

ARL

ARL has successfully made 3D printing filament feedstock from waste MRE bags. nScrypt Ex31:3 fused deposition modeling (FDM) equipment successfully converted the filament into a simple shape.

Filaments also made from water bottles (PET), Styrofoam, scrap polystyrene, polypropylene and HDPE.

rPET rPS

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Polymer AM on the Battlefield-Technical Challenges

ARL

- PET extrusion difficult due to low viscosity of polymer, filament diameter too small- modification to extruder needed (larger nozzle, filament winder and speed controller ordered). Collaborator making PET filament in meantime

- PP filament diameter not consistent- winder should help solve problem

- Styrofoam filaments too brittle- switch focus to high-density polystyrene

- MRE (outer bag) print layers have poor adhesion- working on drying filament, changing bed and printing parameters, work planned also using inner bags (polypropylene)

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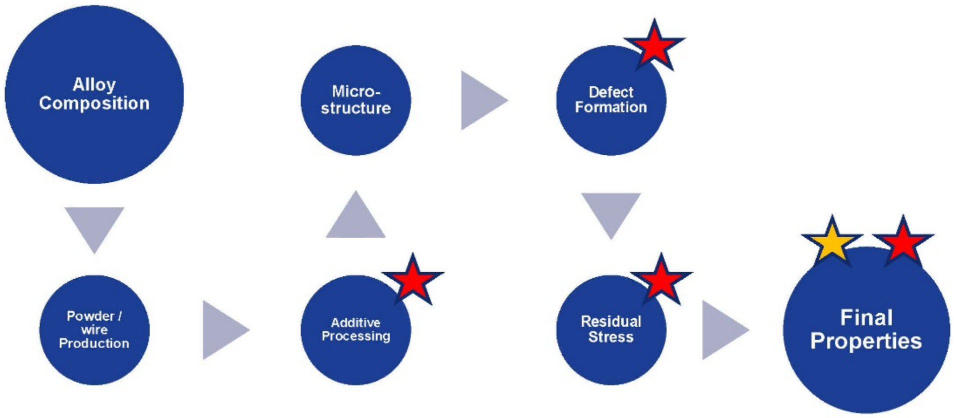
MFPT Community can help here...

ARL



From: http://www.amaze-project.eu/[10]

- In-situ and/or final non-destructive inspection
- Sensors, diagnostics, prognostics if/when part placed into service

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Conclusions

ARL

- Additive manufacturing (polymer 3D printing) is already on the battlefield
- ARLs current work is hoping to prove out the following:
  - Metal AM powder production on the battlefield
  - Sand + Binder AM with traditional foundry methods on the battlefield
  - Polymeric 3D printing using recycled, reclaimed, and scrap materials as feedstock on the battlefield

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3. Role of Processing-Structure-Property Relationships in Developing Certification Protocols for Ti-6Al-4V Components

Todd Palmer
(Pennsylvania State University, Applied Research Laboratory)

A fundamental understanding of processing-structure-property relationships is a key prerequisite to the eventual development and implementation of a certification protocol for additively manufactured (AM) components. One unique aspect of the AM process is the role that geometry plays on these relationships and how it can be integrated into certification. These relationships are defined here for specific directed energy deposition AM processing conditions in Ti-6Al-4V by correlating microstructural features with the resulting static mechanical properties. By concentrating on simple geometries, we can characterize variations in the resulting microstructures and mechanical properties at all locations within the Ti-6Al-4V builds. As a result, the relationships between the processing conditions and the resulting structure and properties of the build are quantified and used in the selection of processing conditions that ensure adequate mechanical properties and performance in the final design. Based on these results, a methodology that establishes fundamental relationships between the AM processing conditions, the microstructural features, and the mechanical properties is under development. As part of this effort, an analysis of the uncertainty in mechanical property data for Ti-6Al-4V AM components and a methodology for identifying minimum design values is being developed.

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Role of Processing-Structure-Property Relationships in Developing Certification Protocols for Ti-6Al-4V Components

T.A. Palmer

Applied Research Laboratory
Department of Materials Science and Engineering
Pennsylvania State University

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Agenda

- Challenges in Certification of Titanium Components
- Developing Process-Structure-Property Relationships in Titanium Alloys
- Impact of Post Processing
- Inspection of AM Components
- Path Forward

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Challenges in Certification of Titanium Components

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Changing the Paradigm Accelerated AM Implementation

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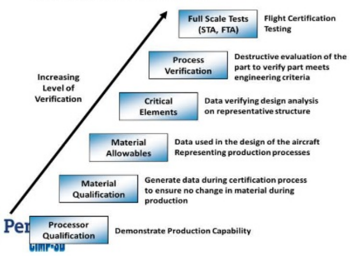
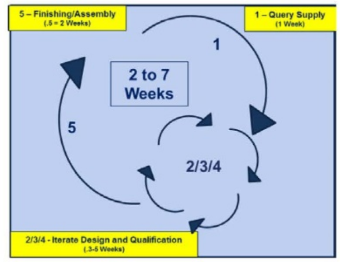
Current Process

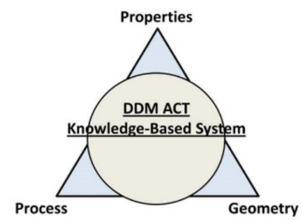
- Linear Building Block Qualification Process
- Engineer Confidence based upon Statistically Substantiated Test Data



On-demand Vision State



- Design Process Incorporates Qualification & Certification
- Engineering Confidence based upon Validated Integrated Models and Simulation Tools



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Designers Rely on MMPDS

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- Various processes
  - Die forging
  - Extrusion
  - Sheet
  - Bar
  - Casting
- Post processing
- Includes various information beyond tensile properties
  - Fatigue behavior
  - Creep behavior
  - Properties versus temperature

UTS
Yield
Elong.

Table 5.4.1.0(f). Design Mechanical and Physical Properties of Ti-6Al-4V Die Forging

Specification	AMS 4928			AMS 4920	
Form	Die forging				
Condition	Alpha-beta processed, annealed			Alpha-beta or beta processed, annealed	
Thickness, in.	≤2.000	2.001-4.000	4.001-6.000	≤2.000	2.001-6.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	135	130	130	130	130
LT	135[a]	130[a]	130	130[a]	130[a]
ST	...	130[a]	130	...	130[a]
F_{ty}, ksi:					
L	125	120	120	120	120
LT	125[a]	120[a]	120	120[a]	120[a]
ST	...	120[a]	120	...	120[a]
F_{cy}, ksi:					
L	...	123	123	...	123
LT	...	128	128	...	128
ST	...	...	...	...	...
F_{su}, ksi	...	79	79	...	79
F_{bru}, ksi:					
(e/D = 1.5)	...	203	203	...	203
(e/D = 2.0)	...	257	257	...	257
F_{bry}, ksi:					
(e/D = 1.5)	...	171	171	...	171
(e/D = 2.0)	...	201	201	...	201
e, percent:					
L	10	10	10	8	8
LT	10[a]	10[a]	10	8[a]	8[a]
ST	...	10[a]	8	...	8[a]
RA, percent:					
L	25	25	20	15	15
LT	20[a]	20[a]	20	15[a]	15[a]
ST	...	15[a]	15	...	15[a]
E, 10^3 ksi	16.9				
E_c, 10^3 ksi	17.2				
G, 10^3 ksi	6.5				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.160				
C, K, and α	See Figure 5.4.1.0				

Example table from Metallic Materials Properties Development and Standardization (MMPDS)

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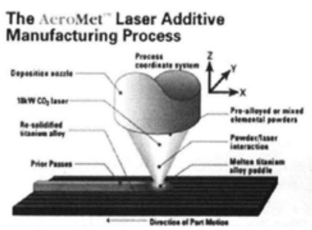
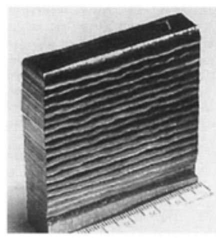
AMS4999A Uses an Extensive Material Property Database

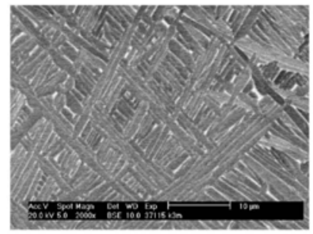
Laser Additive Manufacturing (LAM) process developed by AeroMet

High-power laser powder deposition process (18 kW CO_2)

Until 2005, AeroMet manufactured parts for the aerospace industry







Materials specification with chemistry, heat treatment, and quality assurances

Minimum tensile properties requirements

Qualification of the process and supplier and process parameters

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[1] Kelly et al. (2000) Met. Res. Soc. Symp. Proc. Vol. 625, pp. 3-8.
[2] Kelly et al. (2004) From proceedings of TMS (The Minerals, Metals & Materials Society)

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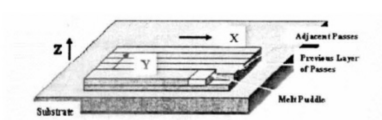
Current AM Allowables are Generally Below Forged Properties

Minimum tensile properties from AMS4999A specification for Ti-6Al-4V AM components

	Tensile Strength		Yield Strength		Elongation
	(ksi)	(MPa)	(ksi)	(MPa)	(%)
Direct Deposited X and Y [1]	129	889	116	799	6
Direct Deposited Z [1]	124	855	111	765	5
Forged Bars and Billets [2]	130	895	120	828	10



Specimen orientation for direct deposited Ti-6Al-4V [1]

[1] Aerospace Material Specification AMS4999 Rev. A. Titanium Alloy Direct Deposited Products 6Al – 4V Annealed
[2] ASTM B348-13. Standard Specification for Titanium and Titanium Alloy Bars and Billets

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Wide Range of Processing Conditions Results in Wide Range of Properties

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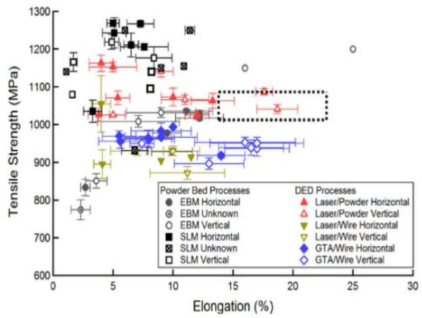
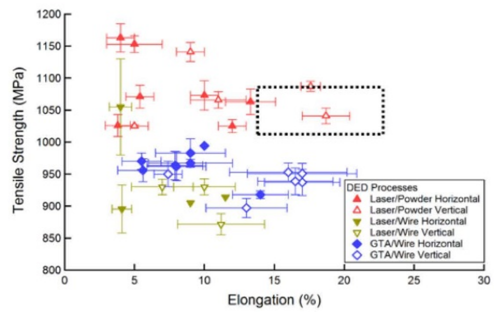
Wide range of mechanical properties reported for AM fabricated Ti-6Al-4V.

PBF and DED Processes



DED Processes



Even with nominally similar processing conditions, mechanical properties reported for AM fabricated Ti-6Al-4V still vary, particularly for elongation.

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Developing Process-Structure-Property Relationships in Titanium Alloys

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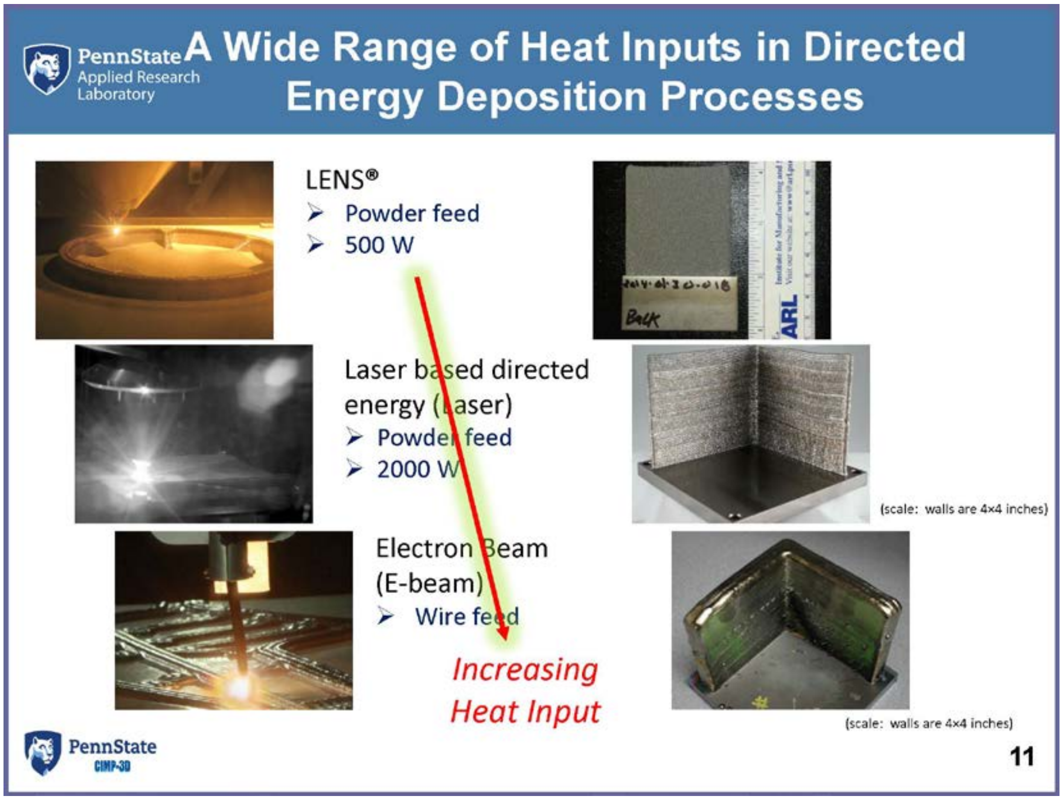

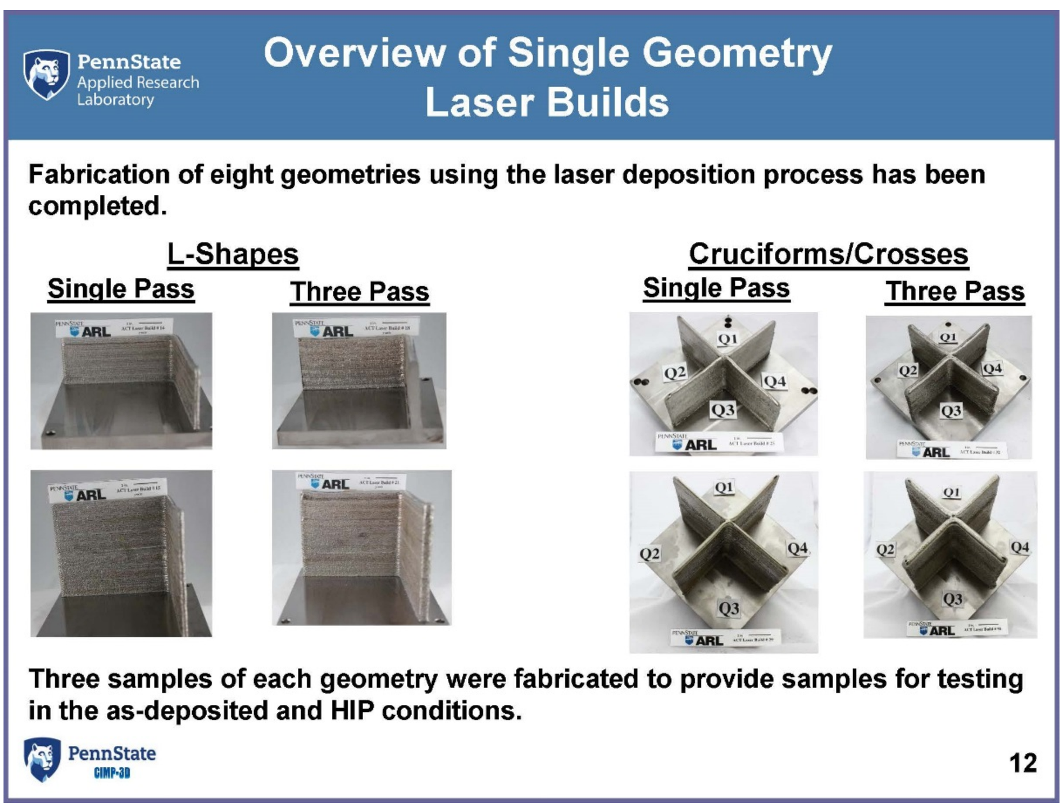

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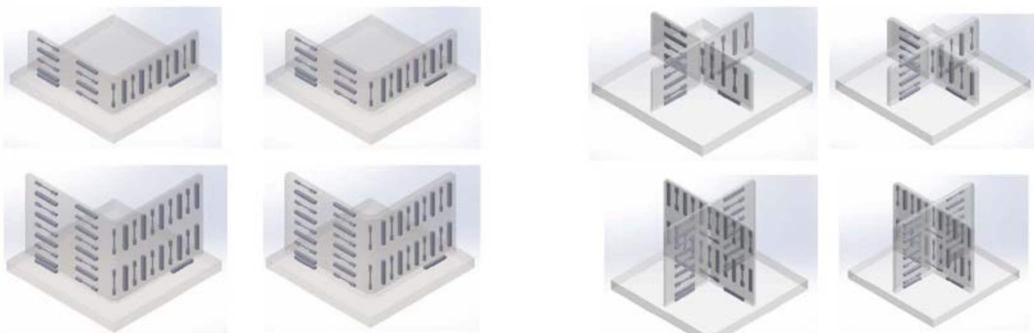
Sample Extraction from Single Geometry Laser Builds

Tensile and metallographic specimens are removed at specific locations in each sample.

L-Shapes — **Single Pass** | **Three Pass**

Cruciforms/Crosses — **Single Pass** | **Three Pass**



Same locations and orientations are tested for the as-deposited, heat treated, and HIP'd samples.

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Overview of As-Deposited Tensile Results

Design[A]	Wall Thickness	Build Height (mm)	Orientation	n[B]	UTS (MPa)	Yield (MPa)	Elongation (%)	Young's Modulus (GPa)
L	Thin (1-pass)	50	Longitudinal	4	1077 +/- 33	959 +/- 32	18 +/- 2	118 +/- 5
			Transverse	5	1012 +/- 20	895 +/- 19	18 +/- 2	117 +/- 6
L	Thin (1-pass)	100	Longitudinal	8	1059 +/- 18	947 +/- 29	18 +/- 4	114 +/- 3
			Transverse	10	1047 +/- 18	933 +/- 18	17 +/- 4	114 +/- 3
L	Thick (3-pass)	50	Longitudinal	4	1118 +/- 10	1015 +/- 12	12 +/- 3	113 +/- 7
			Transverse	5	1042 +/- 29	923 +/- 25	20 +/- 3	113 +/- 4
L	Thick (3-pass)	100	Longitudinal	8	1087 +/- 31	988 +/- 29	20 +/- 3	121 +/- 6
			Transverse	10	1031 +/- 29	924 +/- 26	22 +/- 4	117 +/- 4
C	Thin (1-pass)	50	Longitudinal	4	1043 +/- 10	923 +/- 15	19 +/- 5	115 +/- 2
			Transverse	5	1024 +/- 13	901 +/- 11	15 +/- 5	112 +/- 3
C	Thin (1-pass)	100	Longitudinal	8	1035 +/- 18	910 +/- 17	13 +/- 2	109 +/- 4
			Transverse	12	995 +/- 18	871 +/- 19	19 +/- 3	109 +/- 5
C	Thick (3-pass)	50	Longitudinal	4	1104 +/- 24	994 +/- 33	12 +/- 2	114 +/- 2
			Transverse	5	1072 +/- 29	959 +/- 29	14 +/- 4	113 +/- 5
C	Thick (3-pass)	100	Longitudinal	10	1076 +/- 25	973 +/- 25	20 +/- 3	115 +/- 3
			Transverse	12	1048 +/- 23	938 +/- 22	23 +/- 3	111 +/- 3
			Average Longitudinal	50	1072 +/- 33	961 +/- 40	17 +/- 4	115 +/- 5
			Average Transverse	64	1032 +/- 31	916 +/- 34	19 +/- 4	113 +/- 5
			Average	114	1049 +/- 37	936 +/- 43	18 +/- 4	114 +/- 5
Minimum Grade 5 Ti-6Al-4V (ASTM B358)					895	828	10	–

[A] L designates L-shape wall structure and C designates cruciform shape wall structure

[B] n designates the number of tensile samples tested

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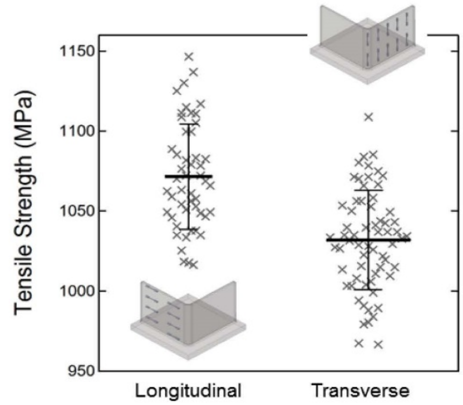
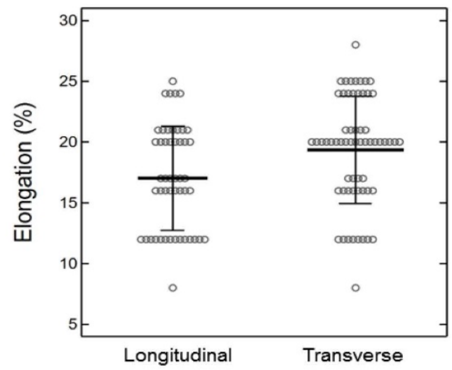
Impact of Orientation on Mechanical Properties





Longitudinally oriented samples exhibited significantly higher tensile strengths than transverse oriented samples.

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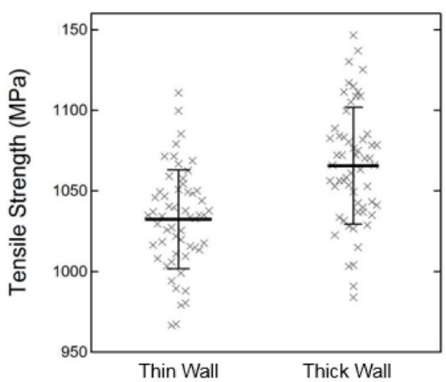
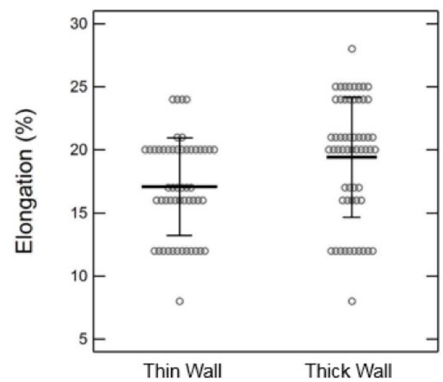
Impact of Wall Thickness on Mechanical Properties





Tensile samples extracted from multi-pass thick wall structures exhibited significantly higher tensile strengths than samples extracted from single pass thin wall structures.

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Impact of Geometry on Mechanical Properties

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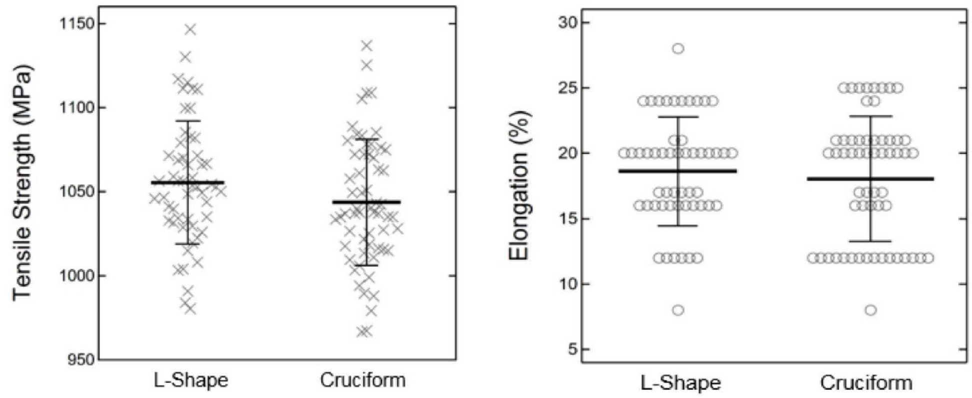

The wall shape was a significant parameter for the single pass thin wall structures. The thin wall L-shapes exhibited a higher tensile strength than the thin wall cruciform structures.

The resulting mechanical properties from the thick wall cruciform and thick L-shape structures, however, were statistically similar.

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Summary of Statistically Significant Relationships

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Factor	Measurement	P-Value	Significant
Wall Thickness	Tensile Strength	< 0.001	Yes
	Elongation	0.006	Yes
Design	Tensile Strength	0.039	Yes
	Elongation	0.449	No
Thickness × Design	Tensile Strength	0.003	Yes
	Elongation	0.659	No

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Primary Microstructural Features in AM Ti-6Al-4V

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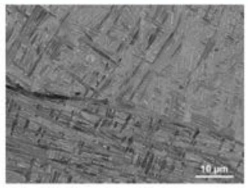
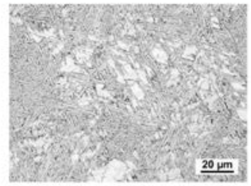
Microstructural features

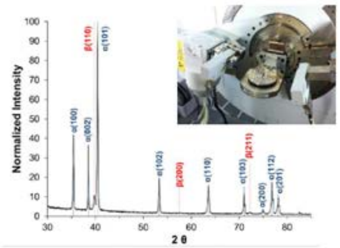
- α lath width
- α/β Phase volume fraction



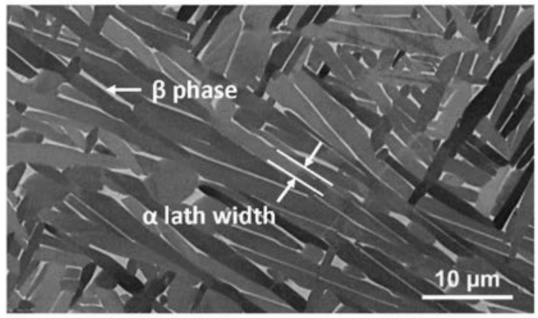
SEM microscopy – backscatter
(Laser based directed energy)



Optical microscopy
(Laser based directed energy)



XRD (x-ray diffraction)



Characteristic Ti-6Al-4V microstructure from AM builds

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Different Part Geometries Produce Different Microstructures at Same Location

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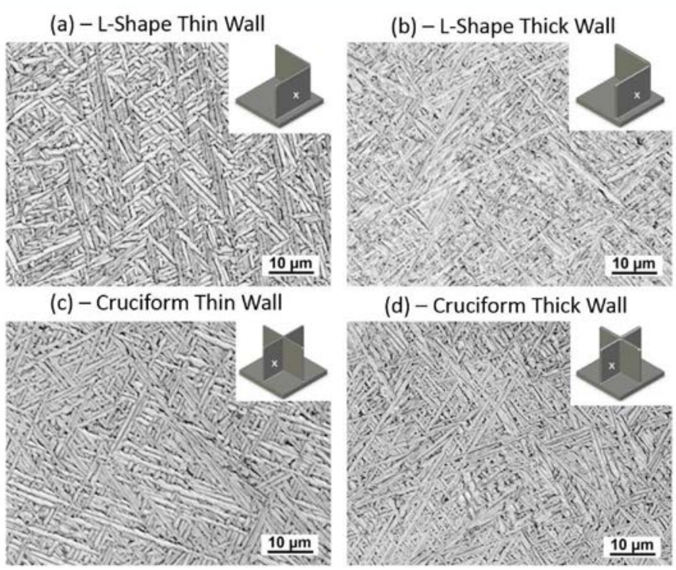

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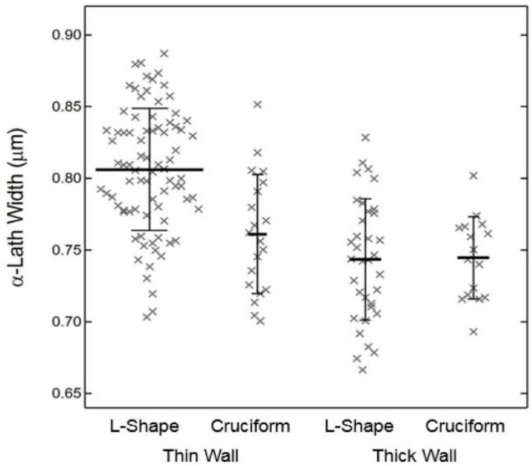
Alpha Lath Width Shows Little Change with Geometry



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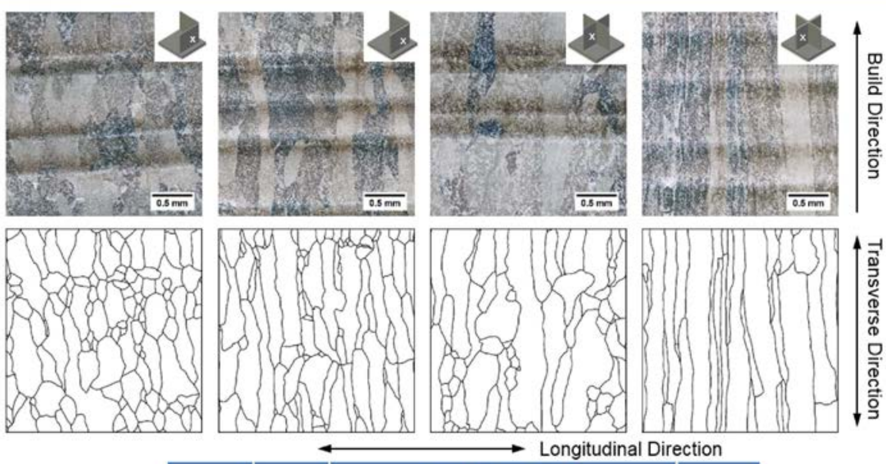
Prior Beta Grain Structure Impacted by Changing Geometry



		Average Grain Intercept (mm^{-1})		
Design[A]	Passes	Longitudinal	Transverse	Ratio[B]
L	1	4.1	2.7	0.66
L	3	4.8	1.4	0.29
C	1	3.5	1.3	0.37
C	3	4.8	0.7	0.15

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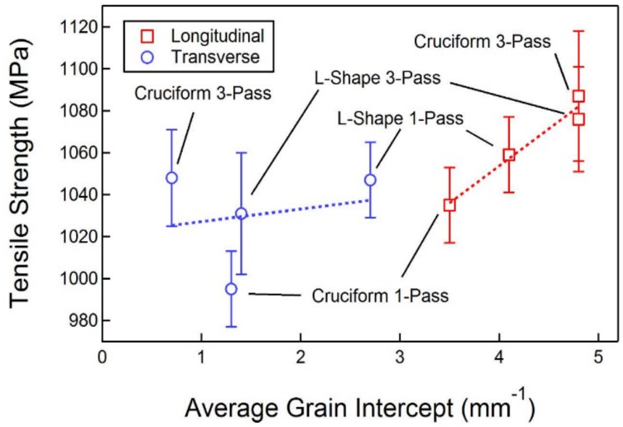
Prior Beta Grain Measurements Show Trends With Tensile Strength



The impact of orientation, wall thickness and wall shape may be explained by the amount of boundary strengthening from the prior β grain boundaries.

Higher tensile strengths were obtained from orientations and wall structures that exhibited a higher number of prior β grain boundary intercepts.

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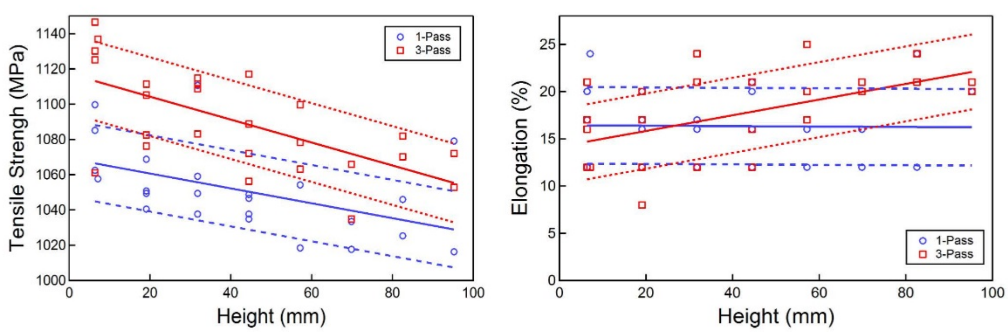
Location Dependence of Mechanical Properties for Longitudinal Specimens



The tensile strengths decreased linearly with increasing height for all the wall structures and for both the longitudinal and transverse orientations.

The elongation measured from the longitudinal tensile samples extracted from the thick wall structures increased linearly with increasing height.

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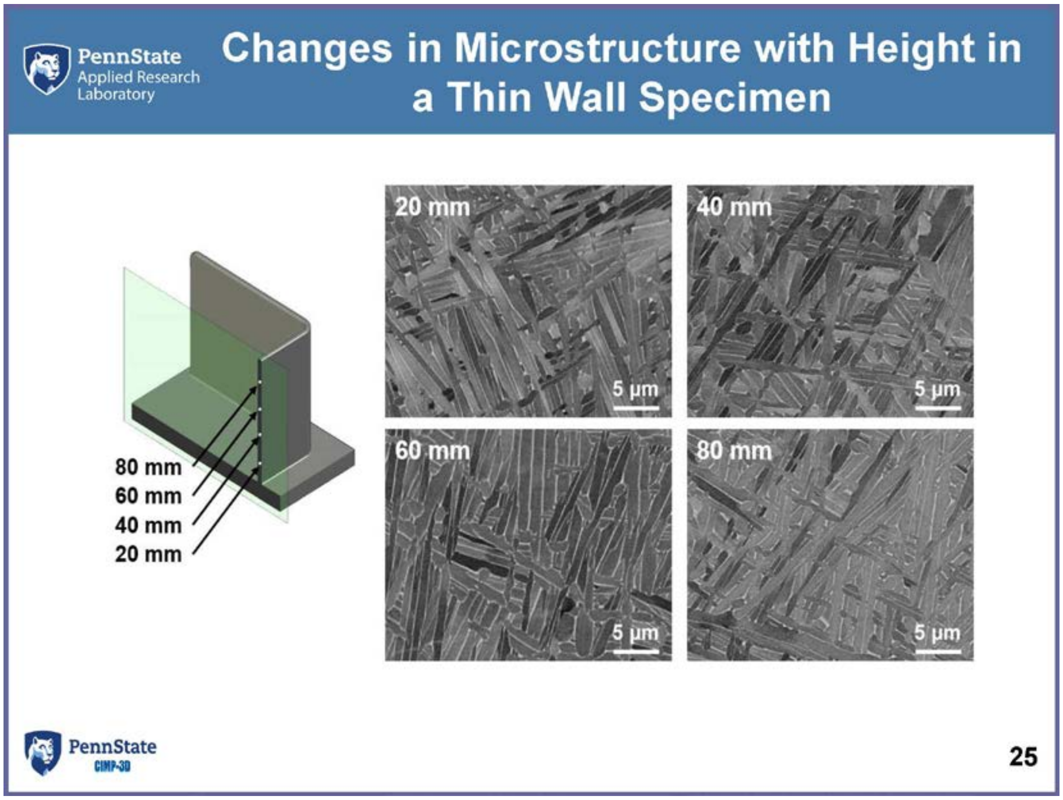

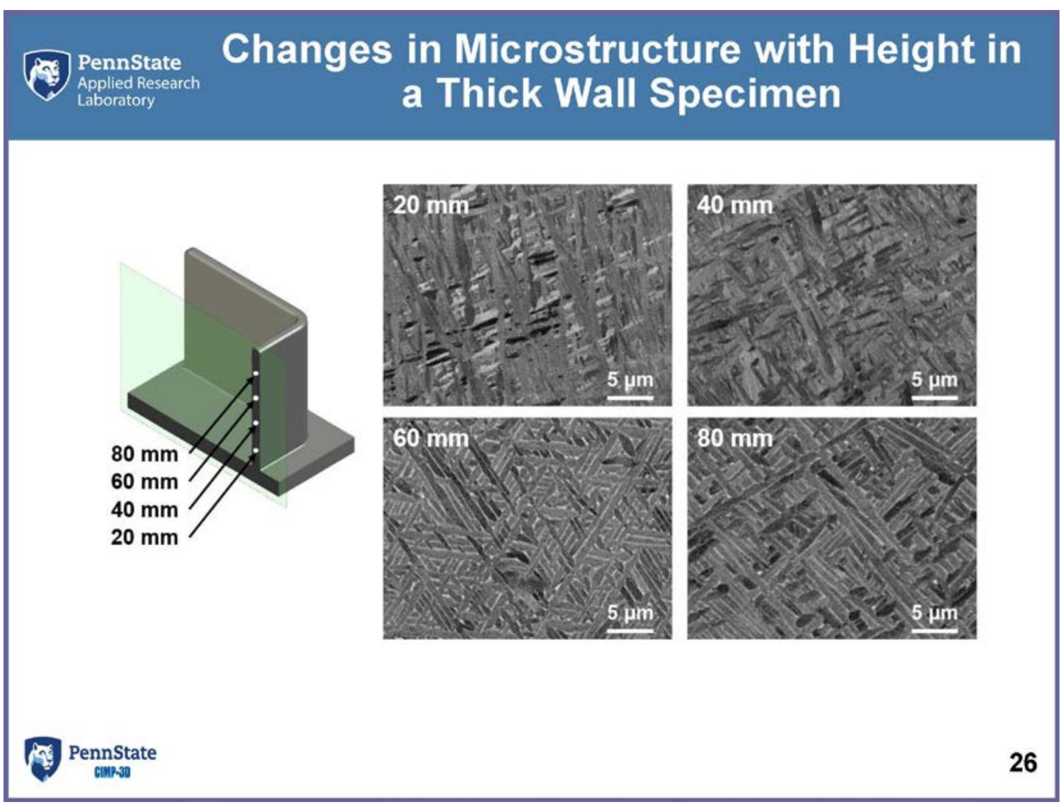

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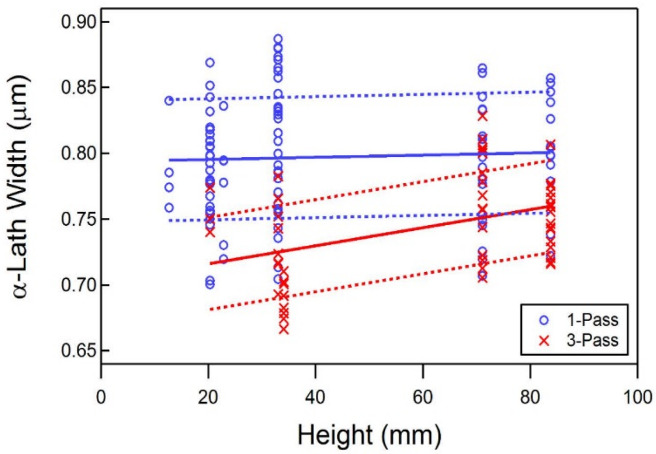
Microstructural Features Demonstrate No Strong Dependence With Location



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Impact of Post Processing

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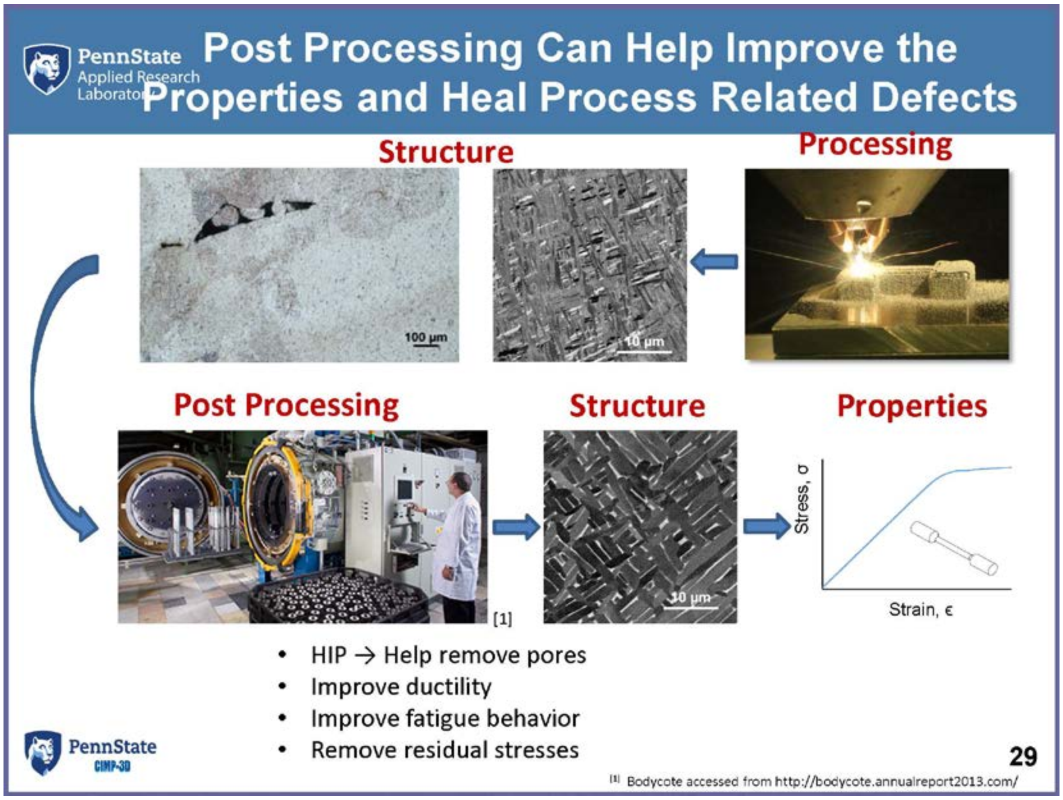

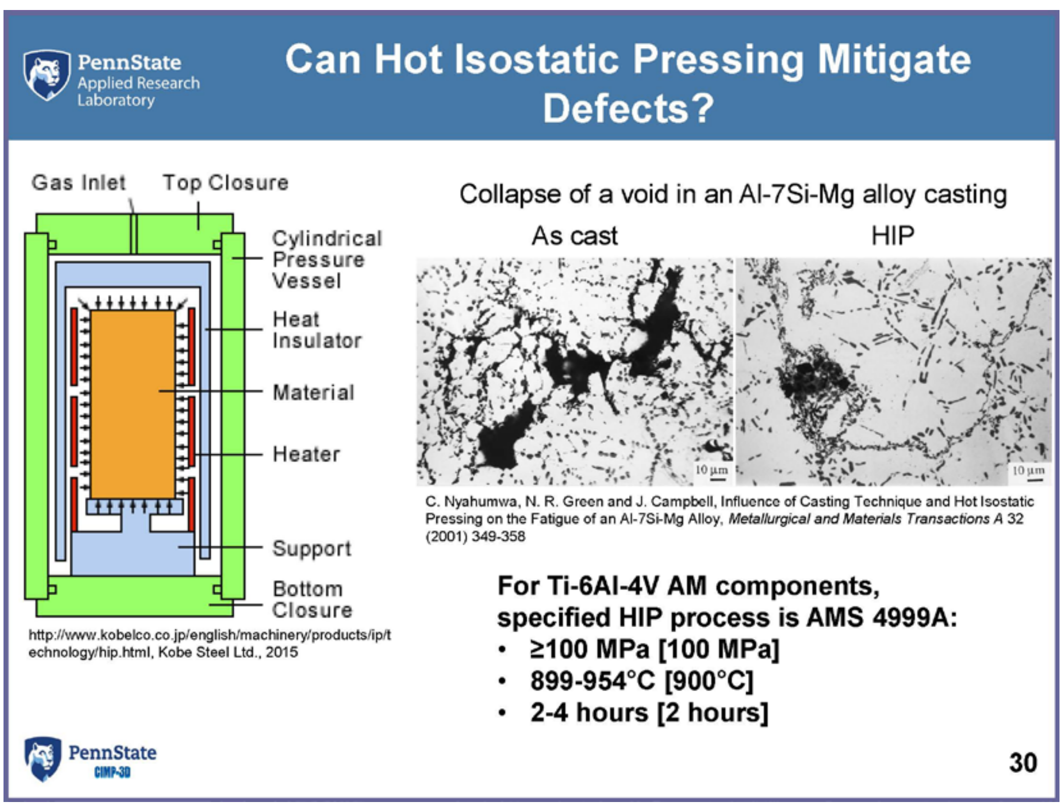

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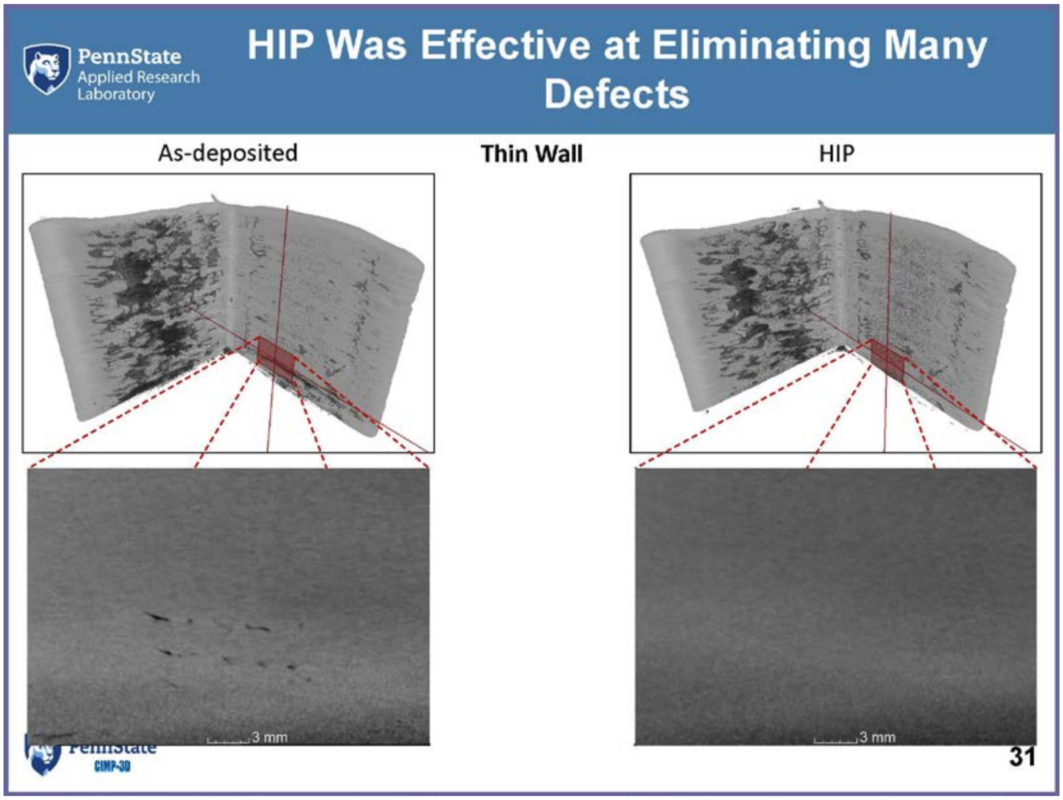

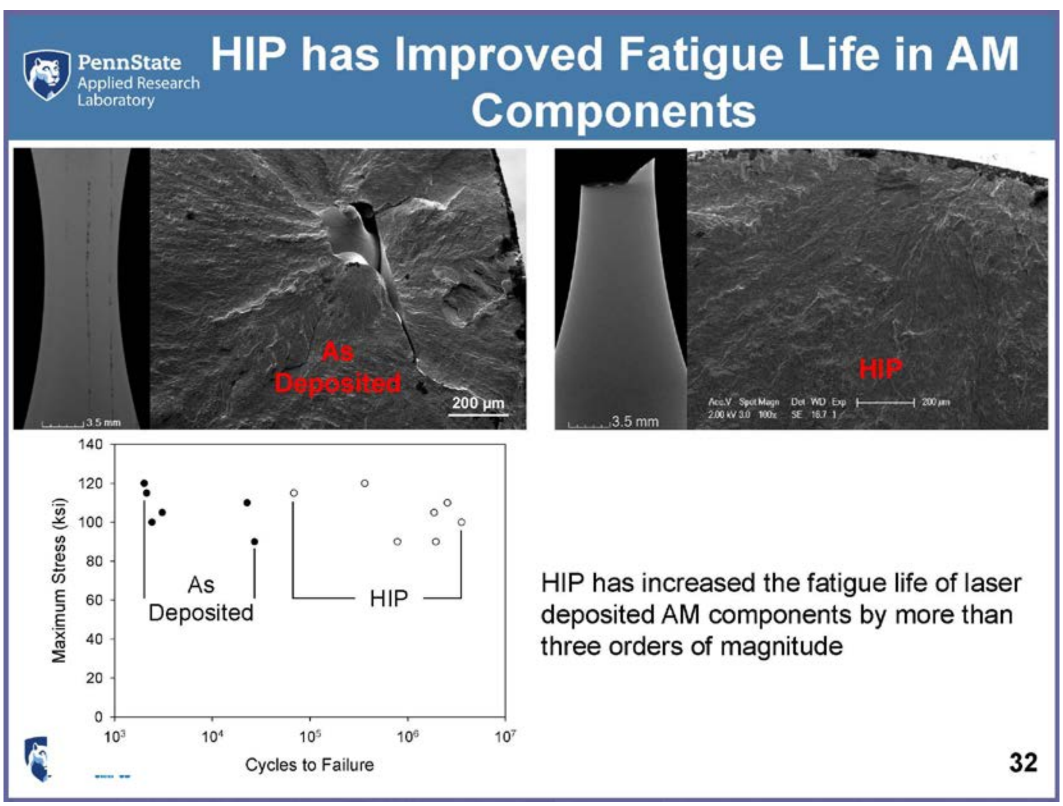

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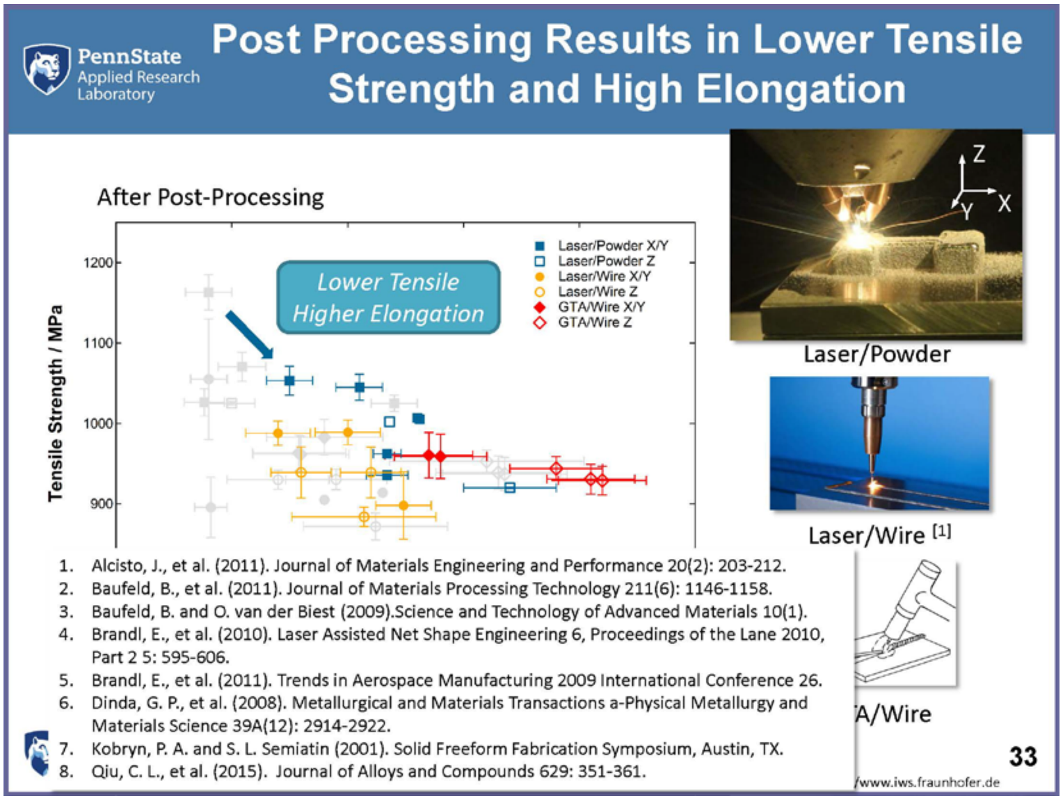

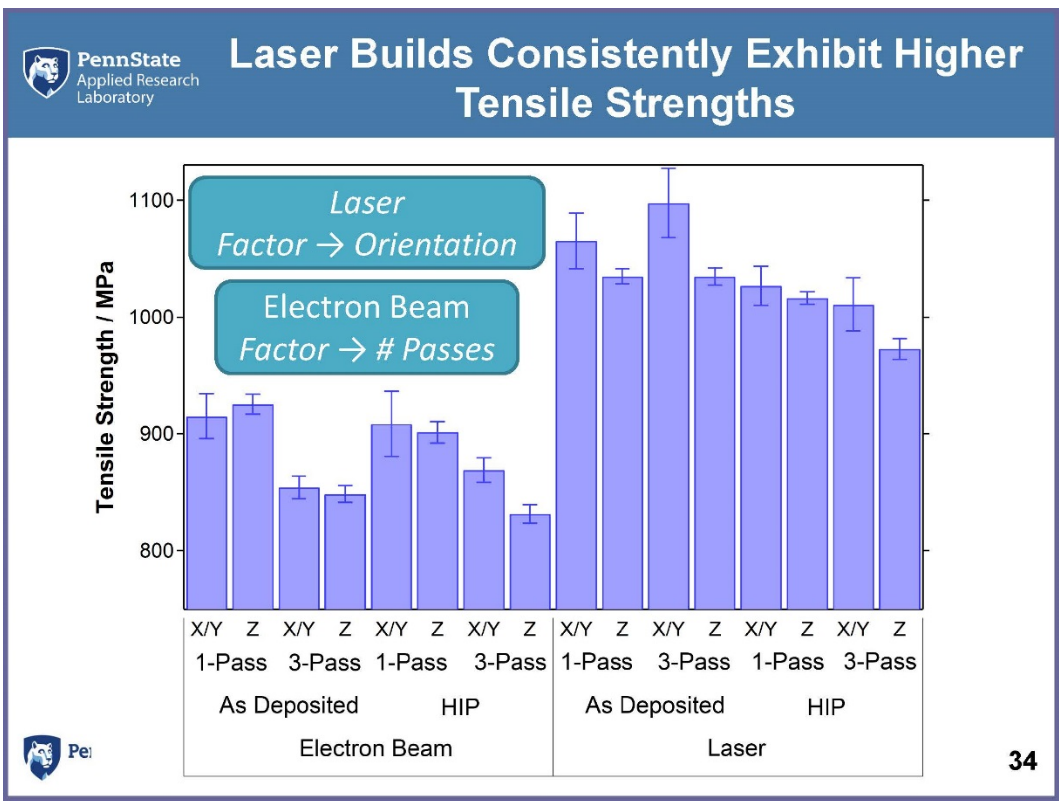

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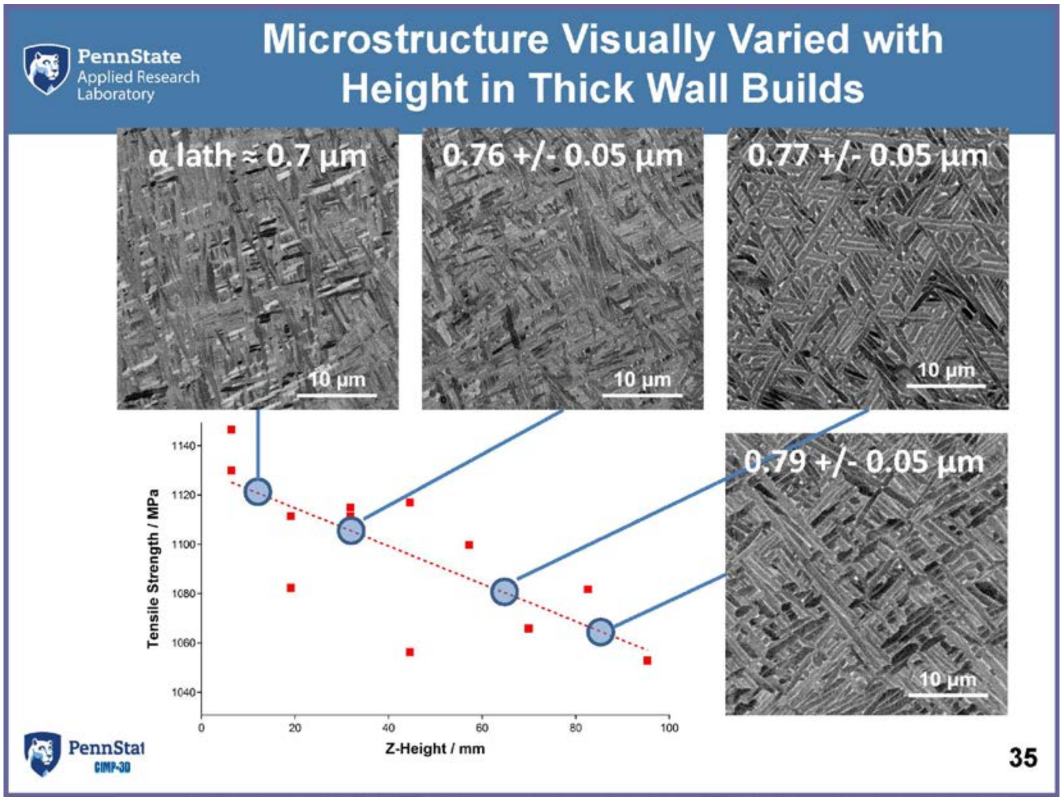

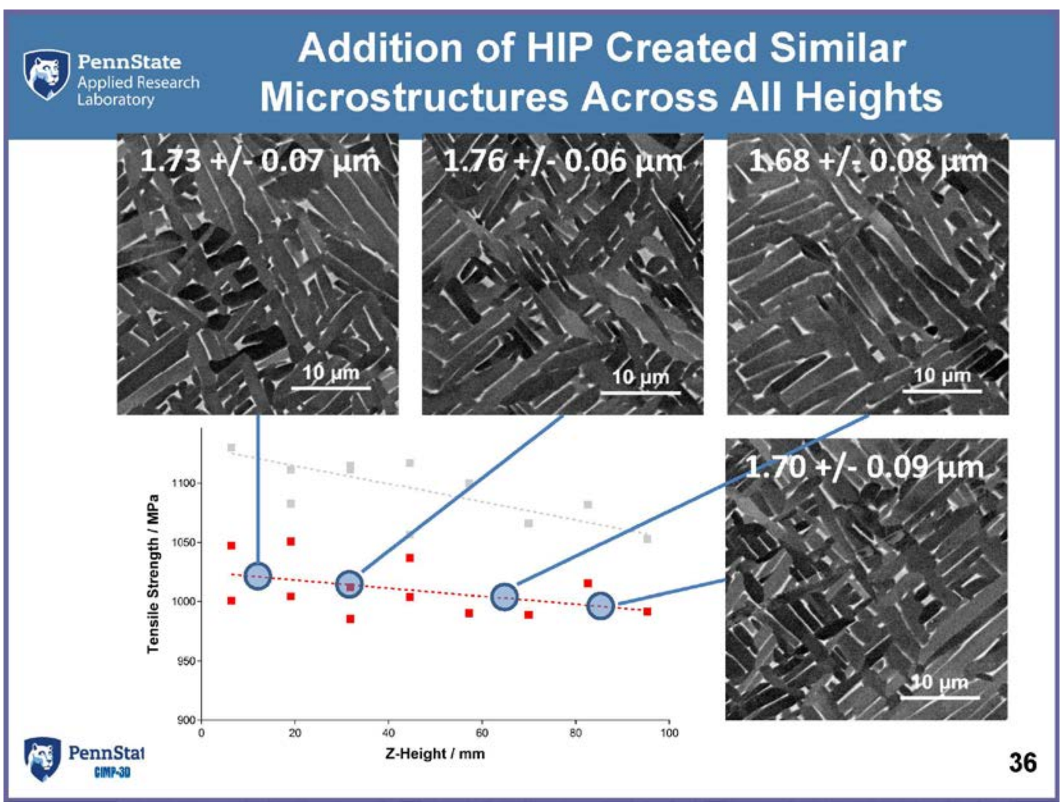

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Inspection of AM Components

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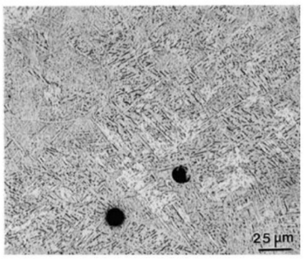
Sources of Defects in Metal-Based Additive Manufacturing

Layer-by-layer manner of the additive manufacturing process produces internal defects similar to those seen in welding and joining processes.

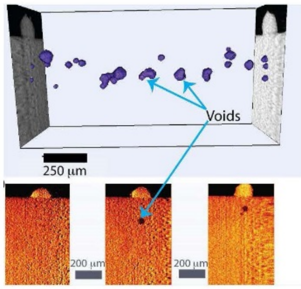
Common defects observed across all material types are process related and caused by changes in bead shape and improper selection and control of processing parameters.

Lack of Fusion Defects

Gas Porosity



Keyhole Collapse



Other defects, i.e. cracking and gas porosity, can be material specific or specific to different processes.

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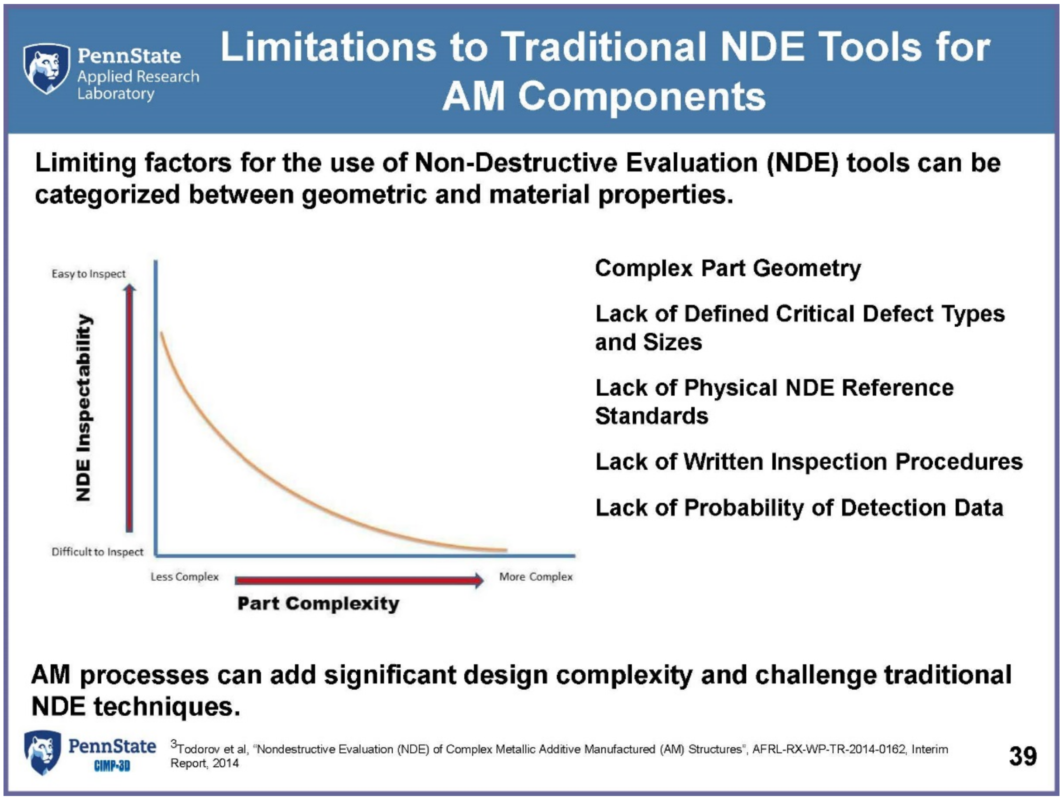
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Limitations to Traditional NDE Tools for AM Components
Limiting factors for the use of Non-Destructive Evaluation (NDE) tools can be categorized between geometric and material properties.
Easy to Inspect
NDE Inspectability
Difficult to Inspect
Less Complex
More Complex
Part Complexity
Complex Part Geometry
Lack of Defined Critical Defect Types and Sizes
Lack of Physical NDE Reference Standards
Lack of Written Inspection Procedures
Lack of Probability of Detection Data
AM processes can add significant design complexity and challenge traditional NDE techniques.
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[3]Todorov et al, "Nondestructive Evaluation (NDE) of Complex Metallic Additive Manufactured (AM) Structures", AFRL-RX-WP-TR-2014-0162, Interim Report, 2014
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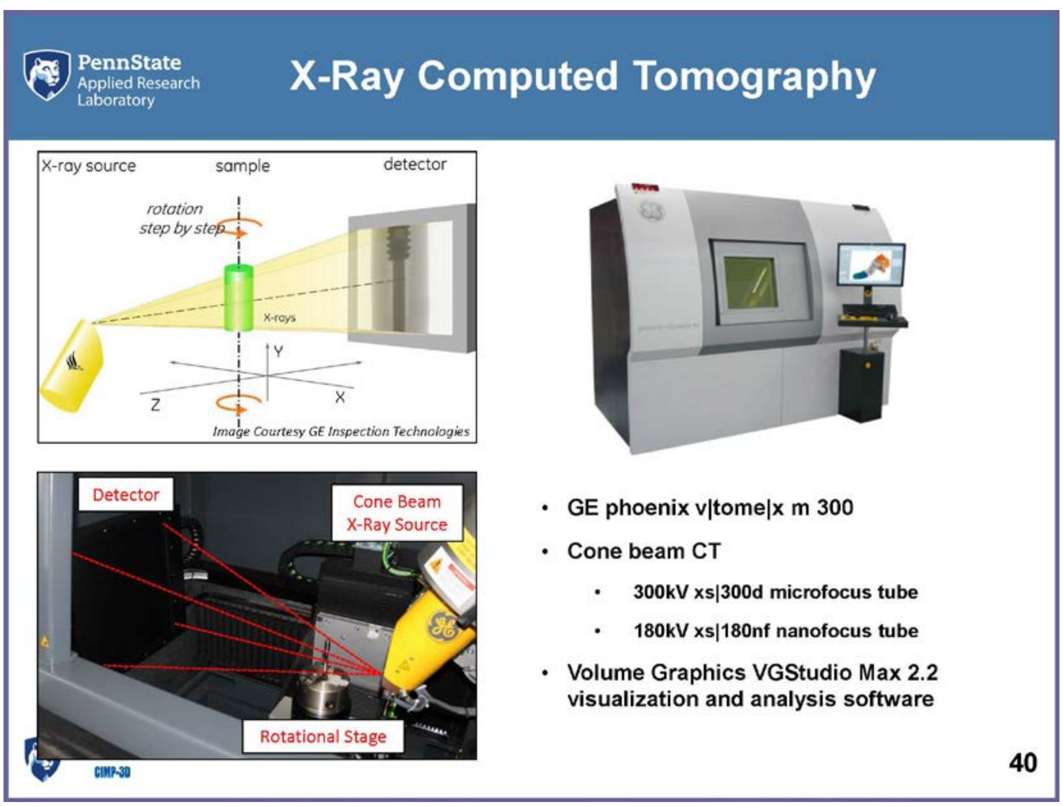
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Applied Research
Laboratory
X-Ray Computed Tomography
X-ray source
sample
detector
rotation
step by step
X-rays
Y
Z
X
Image Courtesy GE Inspection Technologies
Detector
Cone Beam
X-Ray Source
Rotational Stage
• GE phoenix v|tome|x m 300
• Cone beam CT
• 300kV xs|300d microfocus tube
• 180kV xs|180nf nanofocus tube
• Volume Graphics VGStudio Max 2.2 visualization and analysis software
CIMP-3D
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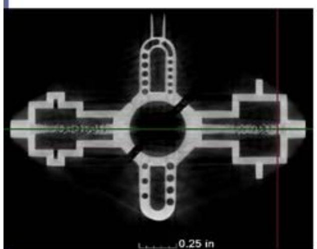
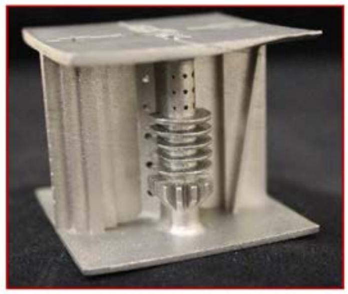
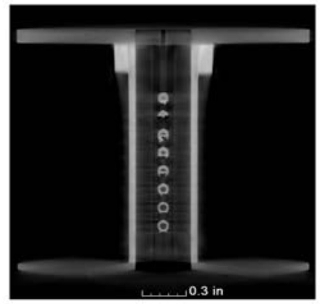
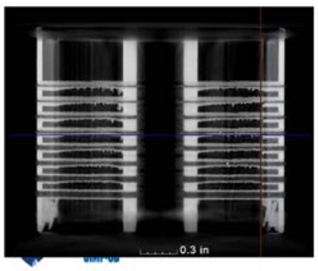
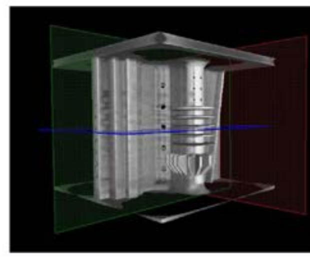
X-Ray CT is a Powerful Tool for Inspecting Complex Internal Geometries











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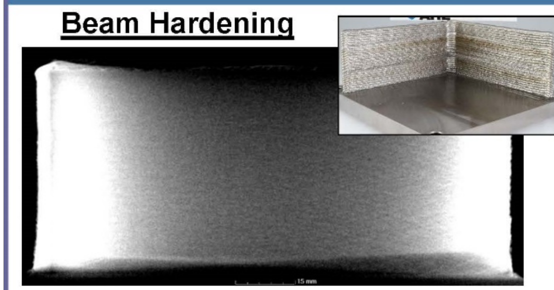
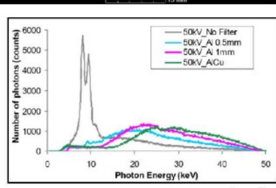
Obtaining Suitable CT Scans and Artifacts in Reconstruction

Beam Hardening

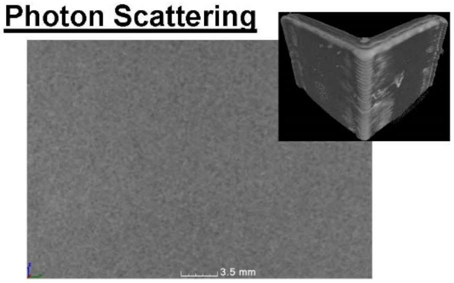


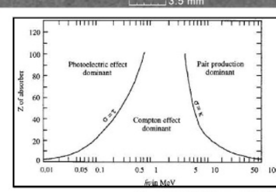


Source: J. P. Kruth et al[1]

- Polychromatic x-ray source
- Lower energy photons preferentially absorbed
- Effect reduced by pre-filters

Photon Scattering





Source: ASTM International[2]

- X-Rays do not follow the expected linear path to the detector
- Results in a greater variation in gray values for a given density condition

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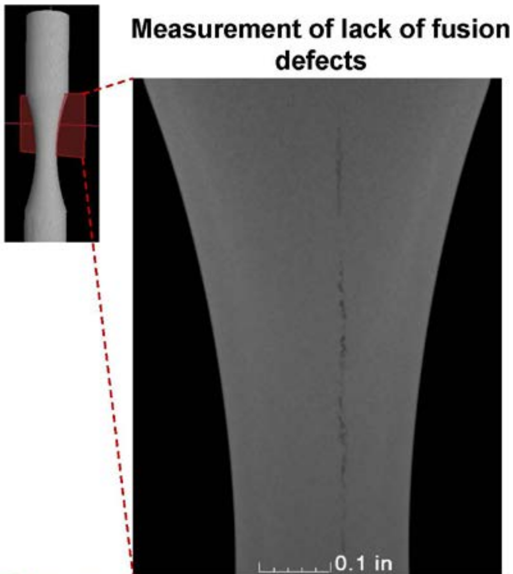
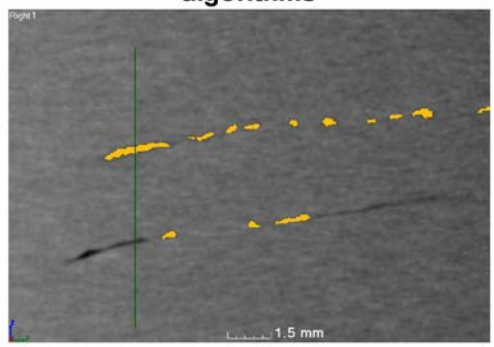
Challenges in Use of Automatic Detection Algorithms

Measurement of lack of fusion defects



Use of automatic defect detection algorithms



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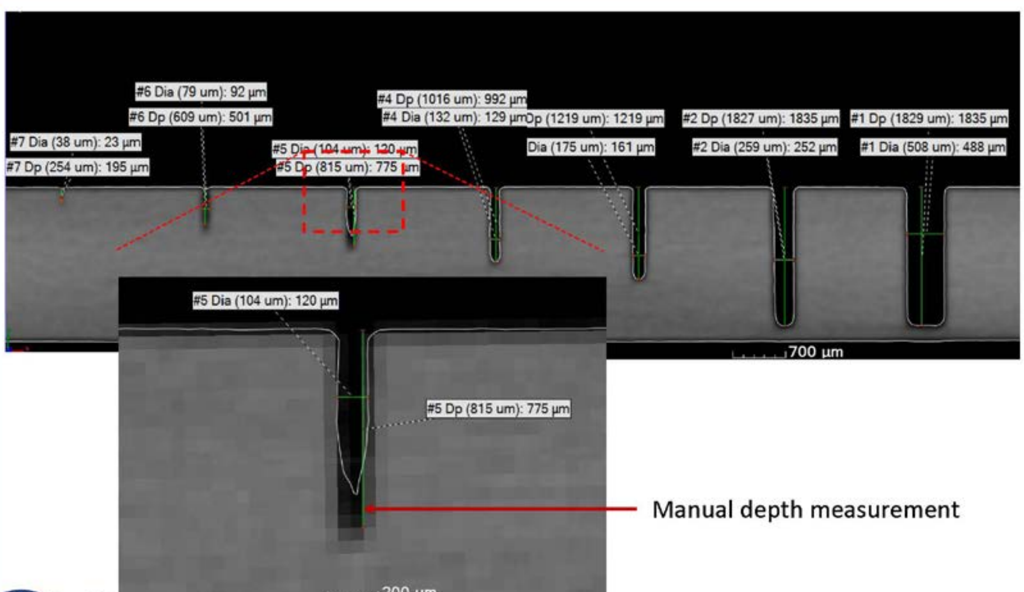
How Accurate are the Measurements Using Analysis Software?



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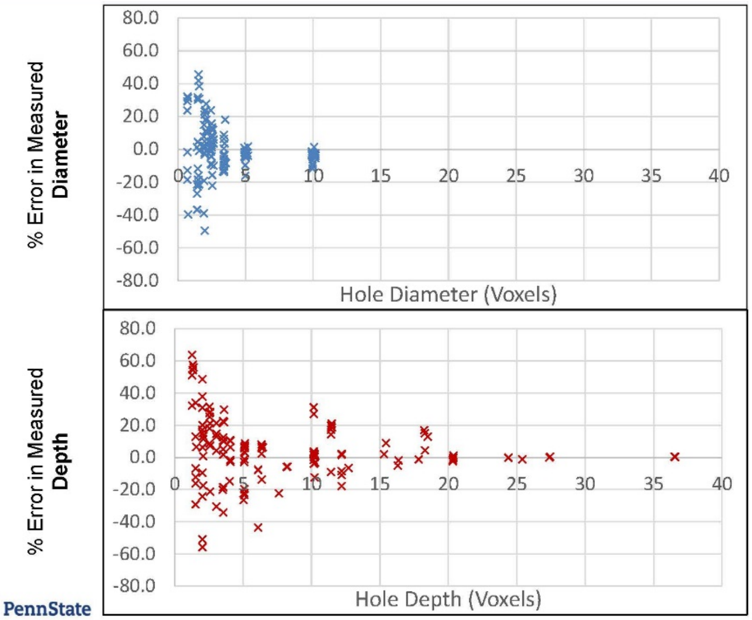
Error in CT Measurements



"Hit" Rate = 137/152

Smaller dimension (diameter or depth) dominated % error

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Path Forward

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What are the Challenges for Certifying AM Parts?

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- Lack of material property database or pedigreed data
- Incomplete knowledge of the role of processing on properties
- Anisotropy in the microstructure and mechanical properties
- Unknown relationships between properties and geometries

➢ *Since AM is producing finished parts → Impossible to provide certification/data for all possible geometries*

➢ *Need* to develop relationship knowledge base

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Relationships between Design-Processing-Structure-Properties-Performance

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The interrelationships between design, processing, structure, and performance are complicating the certification of AM Ti-6Al-4V components.

Design

Geometries and Features

Breakdown of Part Features

Material Property/Feature Relationships

Processing

Definition of Essential Variables

Processing/Structure Relationships

Quantification of Processing Variable Uncertainty

Material Properties

Development of Structure/ Property Relationships

Impact of Features on Material Properties

Quantification of Material Property Uncertainty

Product and Performance

Assign Reliability to Properties and Analysis

Validate Global Properties

Verify Design Requirements

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Certification of Additive Manufactured Components

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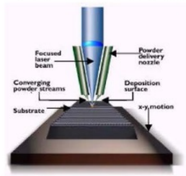
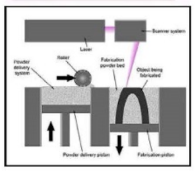
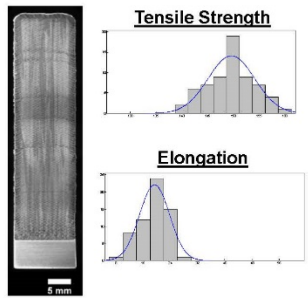
Direct Fabrication of Complex Components





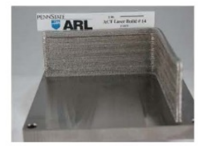
- Small lot sizes (Lot of 1)
- Complex processing conditions
- Undeveloped process and quality controls

Challenges to Certification and Qualification



- Lack of processing/structure/ property relationships
- Lack of material property database or design allowables
- Unknown impact of complex geometries on material properties

New Approaches for Additive Manufacturing



- Link geometric features and important processing variables
- Knowledge-based expert system
- Use canonical features to develop property data base

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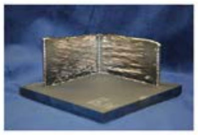
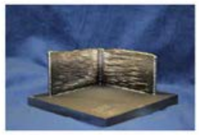
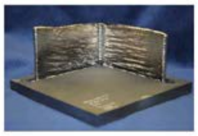
Overview of Single Geometry Electron Beam Builds

L-Shapes

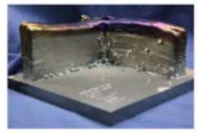
Single Pass

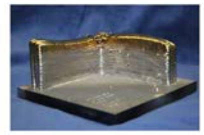


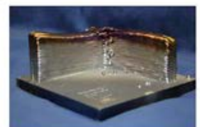




Three Pass







Electron Beam Processing:

- Current, mA : 95 (peak)
- Voltage, kV : 40
- Min Vacuum: 1 uT
- Working Distance: 9.75"
- Wire Feed Speed: 225 ipm
- Travel Speed:30 ipm (max)

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Comparison Between Laser and Electron Beam Deposition

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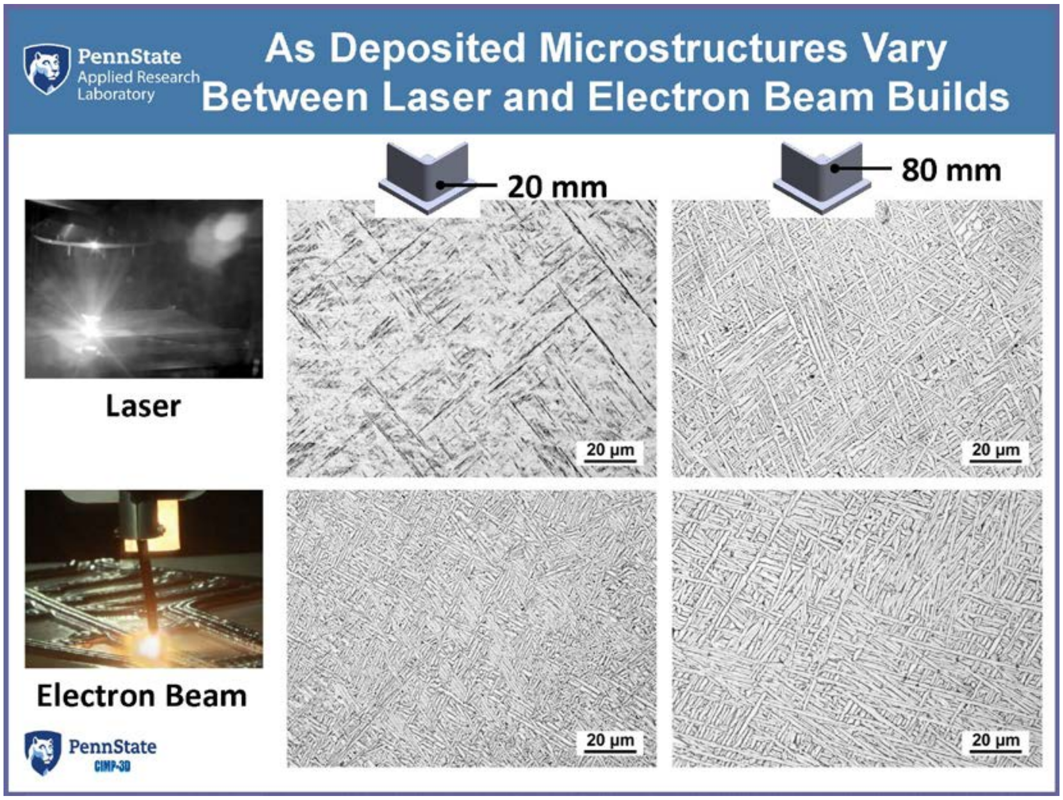

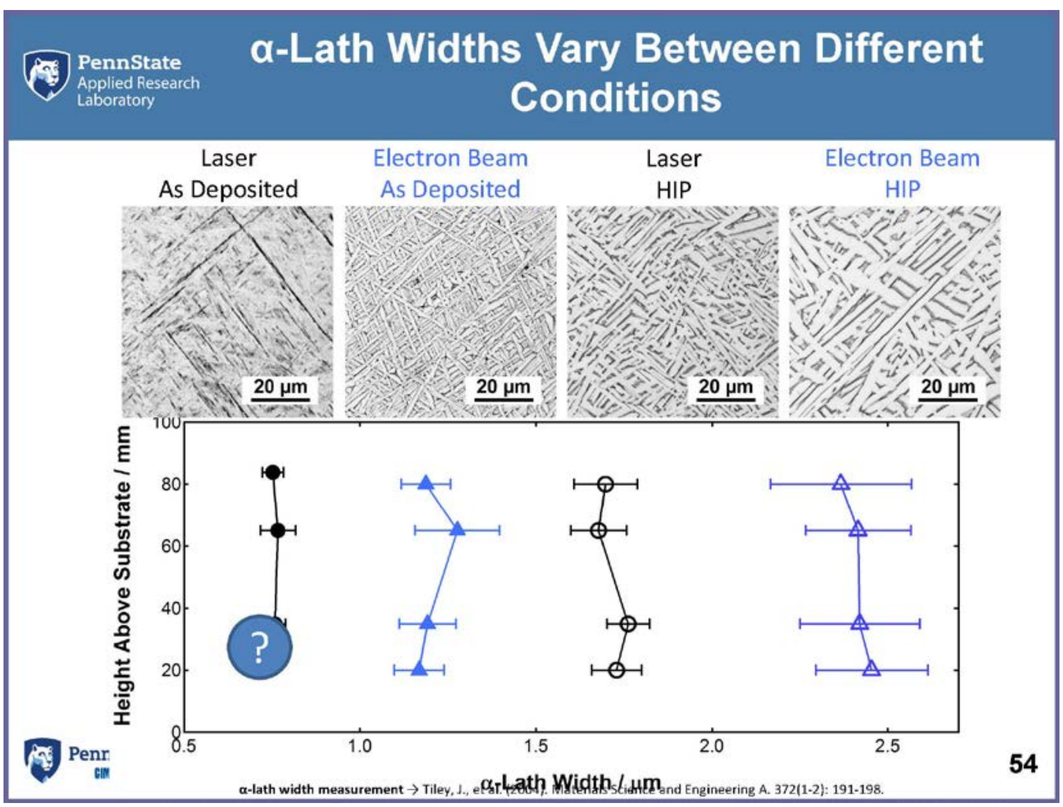

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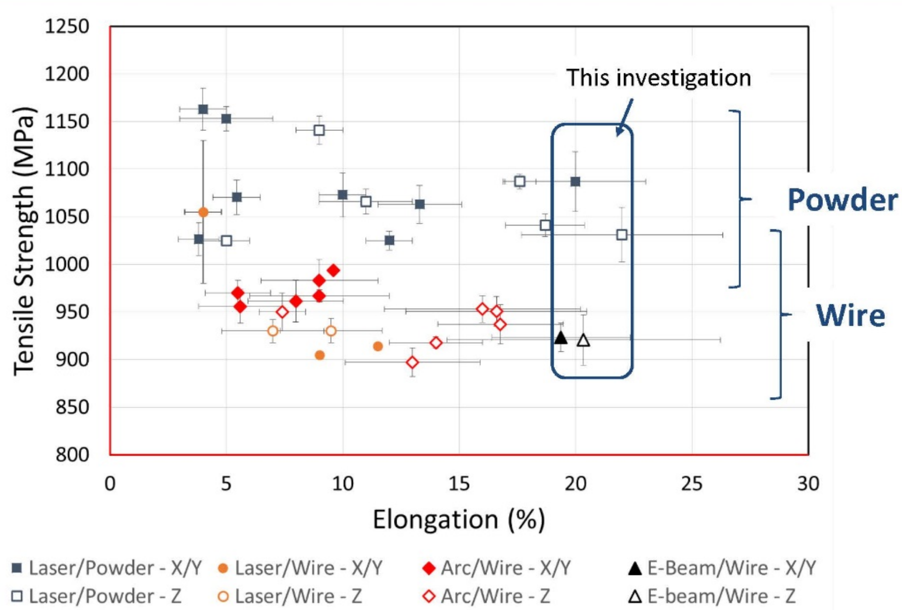
Laser Powder Builds Display Higher Strengths than Electron Beam Wire Builds



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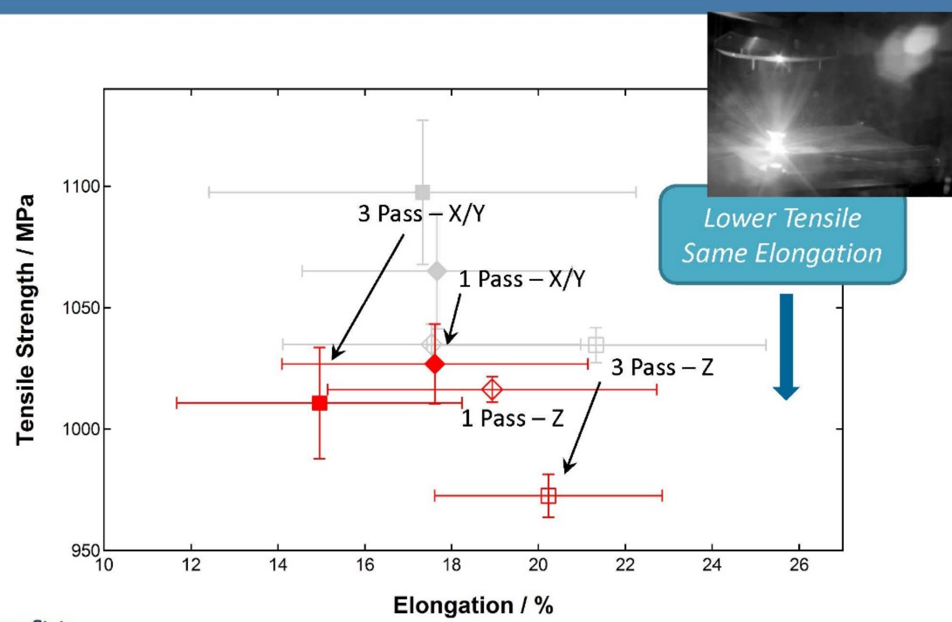
Tensile Strengths Decrease after HIP in Laser Builds



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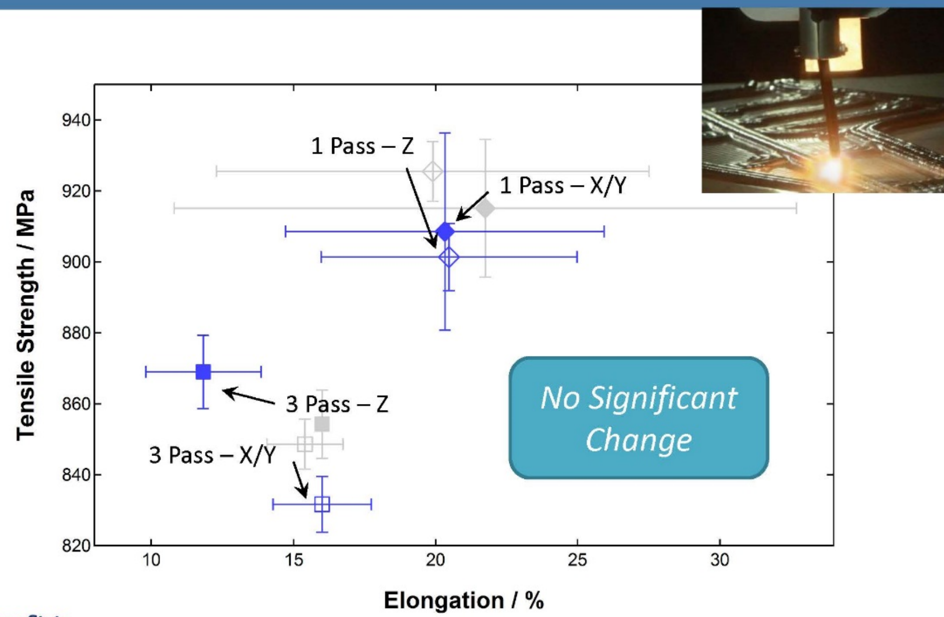
Tensile Strengths After HIP for the Electron Beam DED Builds Show No Change



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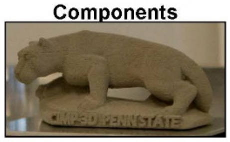
Categorization of Geometric Complexity in AM Components

Additive manufacturing capable of producing parts with a wide range of geometric complexity.

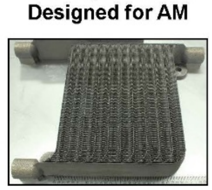
Group 1: Simple Components



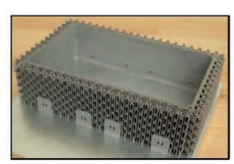
Group 2: Optimized Components

Group 3: Components with Embedded Features

Group 4: Components Designed for AM



Group 5: Lattice Structures



Todorov et al, "Nondestructive Evaluation (NDE) of Complex Metallic Additive Manufactured (AM) Structures", AFRL-RX-WP-TR-2014-0162, Interim Report, 2014

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Impact of AM Microstructure on NDE Response

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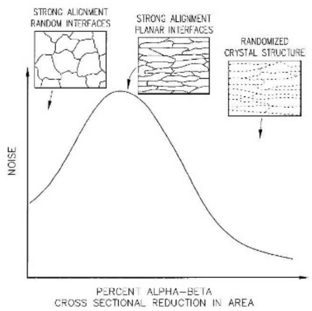
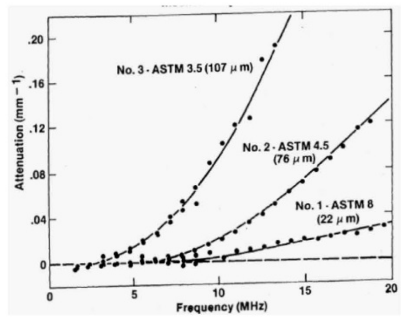


Relative noise during ultrasonic inspection of Titanium alloys as a function of final hot working[1]



Ultrasonic attenuation in Inconel alloy 718 as a function of frequency for various grain sizes[2]

Example Ti-6Al-4V macrostructure from a laser DED build

- Large grains and anisotropic grains are known to cause preferential attenuation of ultrasonic waves
- Layer-by-layer nature of additive manufacturing promotes epitaxial grain growth

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[1]Gorman, M.D., Woodfield, A. P., "Processing of titanium-alloy billet for improved ultrasonic inspectability", EP 1136582 A1, 2001.
[2]Telschow, K.L., "Noncontacting NDE for Materials Characterization", Idaho National Engineering Laboratory, 1995.

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Range of Surface Finishes are Possible in AM Processing

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- A wide range of surface finish is produced in the as-built condition with various additive techniques
- NDE methods that are most sensitive to surface finish include visual testing, liquid dye penetrant testing, magnetic particle testing, eddy current testing and ultrasonic testing
- Some surface finishes will prevent the use of these methods
- As a near-net shape process, AM will usually require some post-process machining that would enable a wider range of methods to be employed

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4. Additive Manufacturing Characterization Utilizing X-ray Computed Tomography

Jennifer Sietins
(Army Research Laboratory, Weapons and Materials Research Directorate)

X-ray computed tomography (CT) is a valuable technique for quality control measures, part inspection, dimensional analysis, microstructural characterization, and void identification and quantification. This nondestructive characterization technique allows for 3D imaging that readily captures defects and voids on the conditions that the attenuation, which is approximately related to the material density, is distinctly different from the surrounding material, and the resolution is sufficient for the feature or defect sizes of interest. This work summarizes the CT capabilities at the Army Research Laboratory, with a specific emphasis on the characterization of 3D-printed structures. Analysis examples will include quantification of tolerance differences between the designed and manufactured parts, void sizes and distributions, in-situ compression tests for brittle and elastic truss structures, and mechanical behavior simulations for meshes generated from the CT scan data. These tools can enable faster process optimization time frames and ensure that the final part does not have voids above a critical size prior to fielding.

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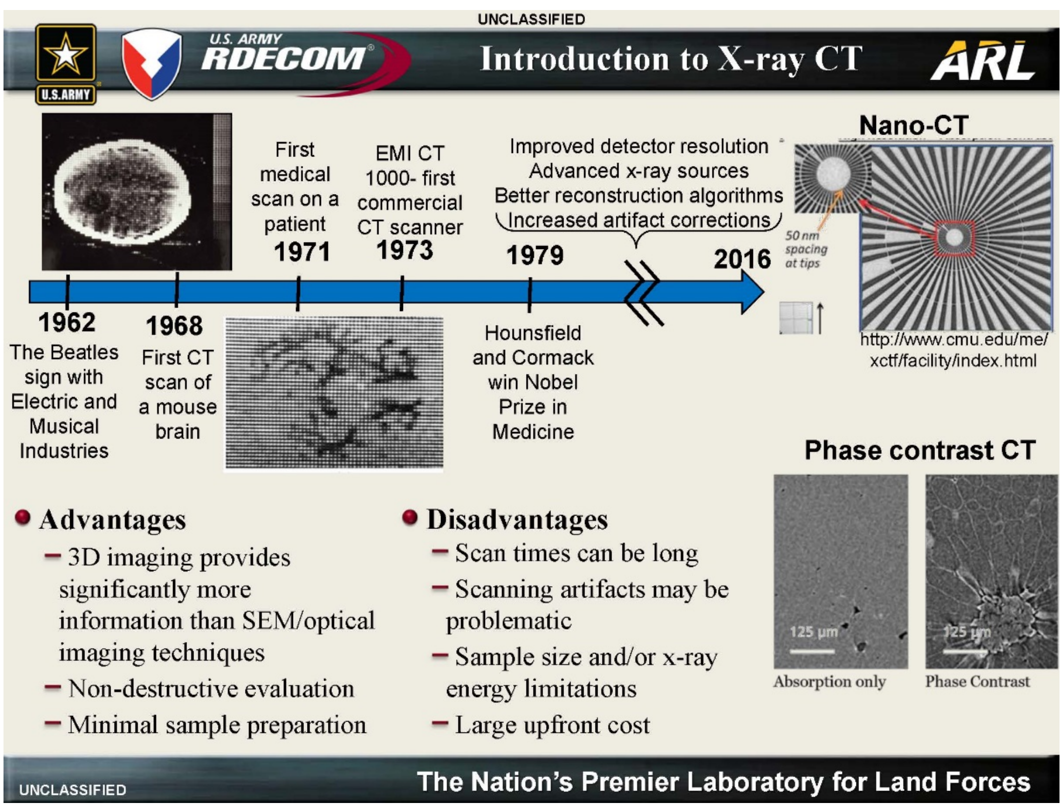

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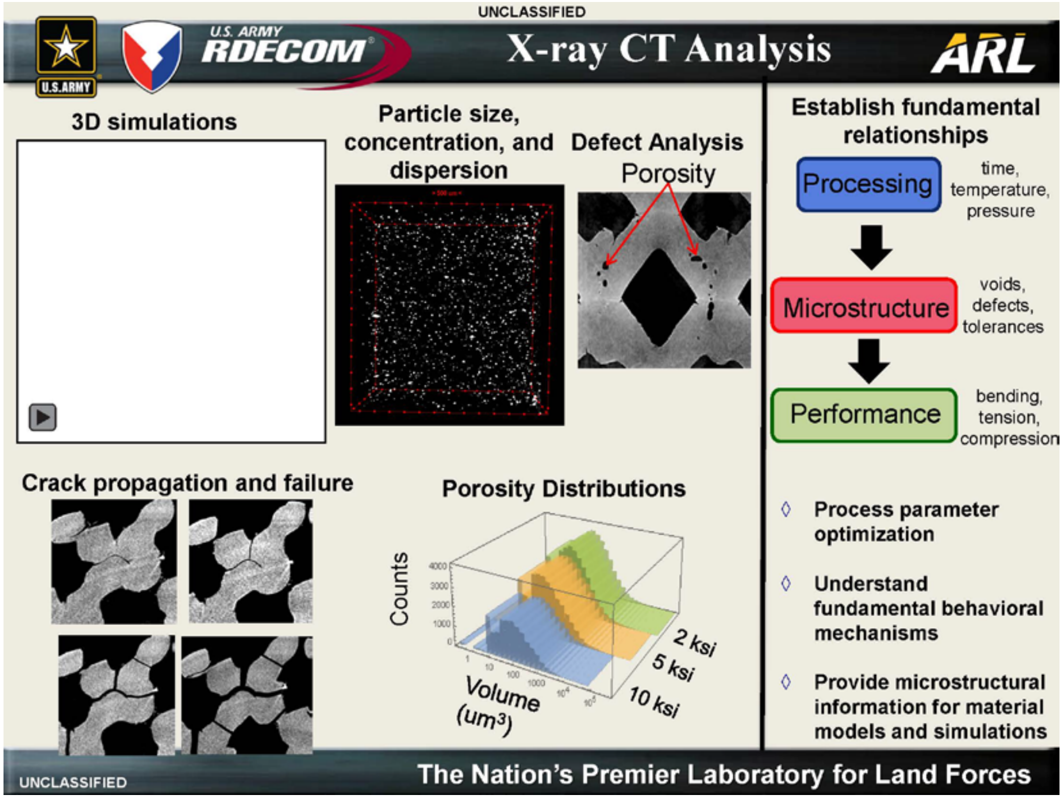

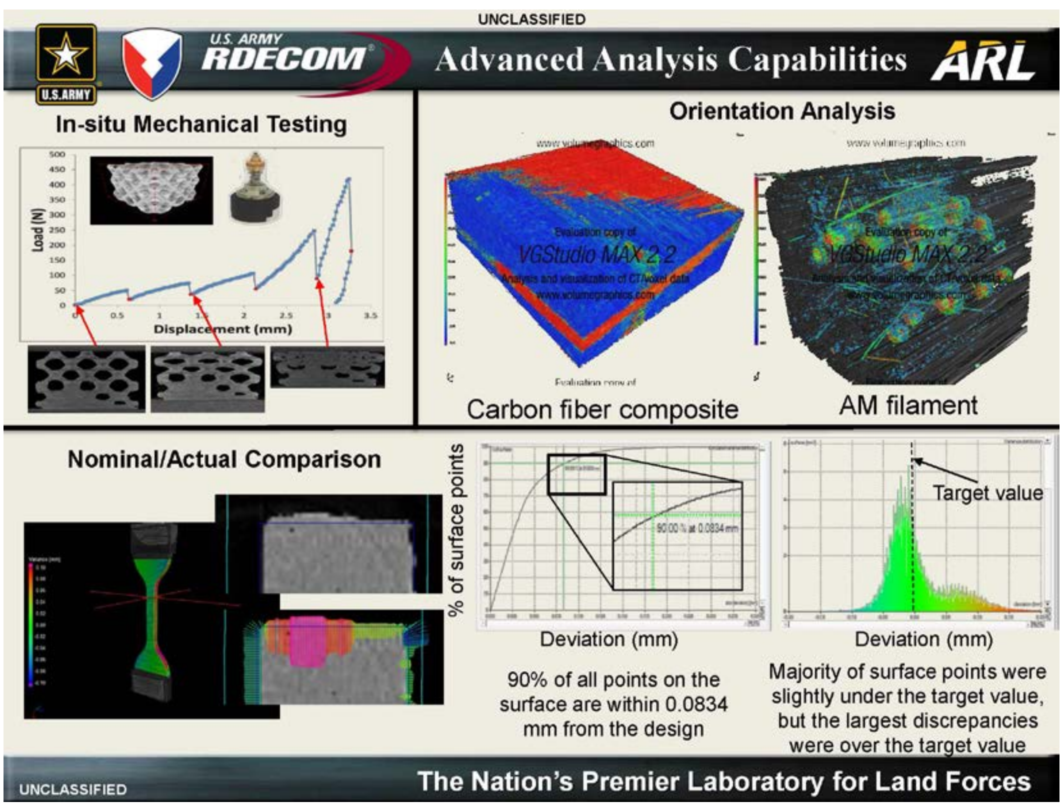

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ARL CT Systems

ARL

Bruker Skyscan 1172

Power: 20-100 kV, up to 10W
Sample size < 26 mm
Minimum voxel size: 0.5 um
Resolution: approximately 5 um

Zeiss Xradia 520 Versa

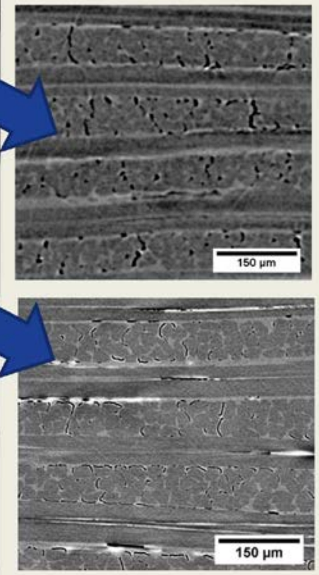
Power: 30-150 kV, up to 10W
Sample size < 300 mm
Minimum voxel size: 70 nm
Resolution: 0.7 um

Phase contrast enhancement

NorthStar X5000

Power: 25-225 kV, up to 320 W
450 kV, 700 or 1500 W
Sample size 16”
Minimum voxel size: ~20 um

Non-cabinet system
Enhanced speed detector



Ultra-High molecular weight polyethylene

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Analysis Example 1:
Nominal/Actual Comparison

Analysis Example 2:
Porosity Quantification

Analysis Example 3:
In-Situ Mechanical Testing

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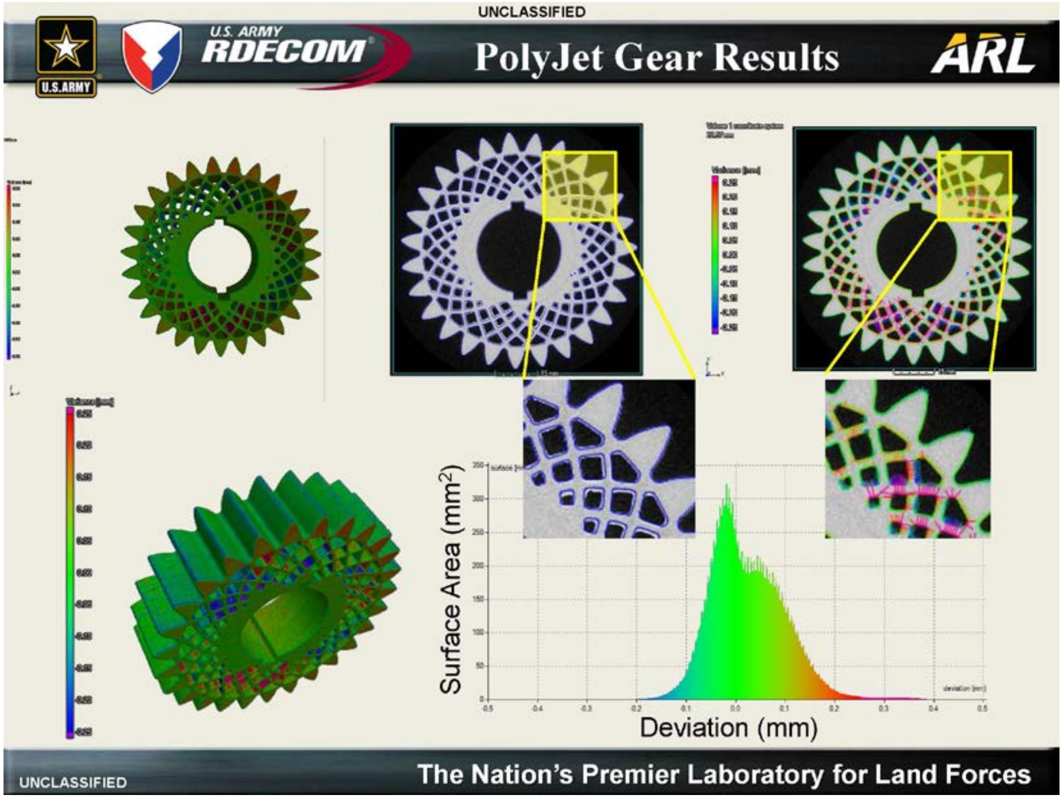

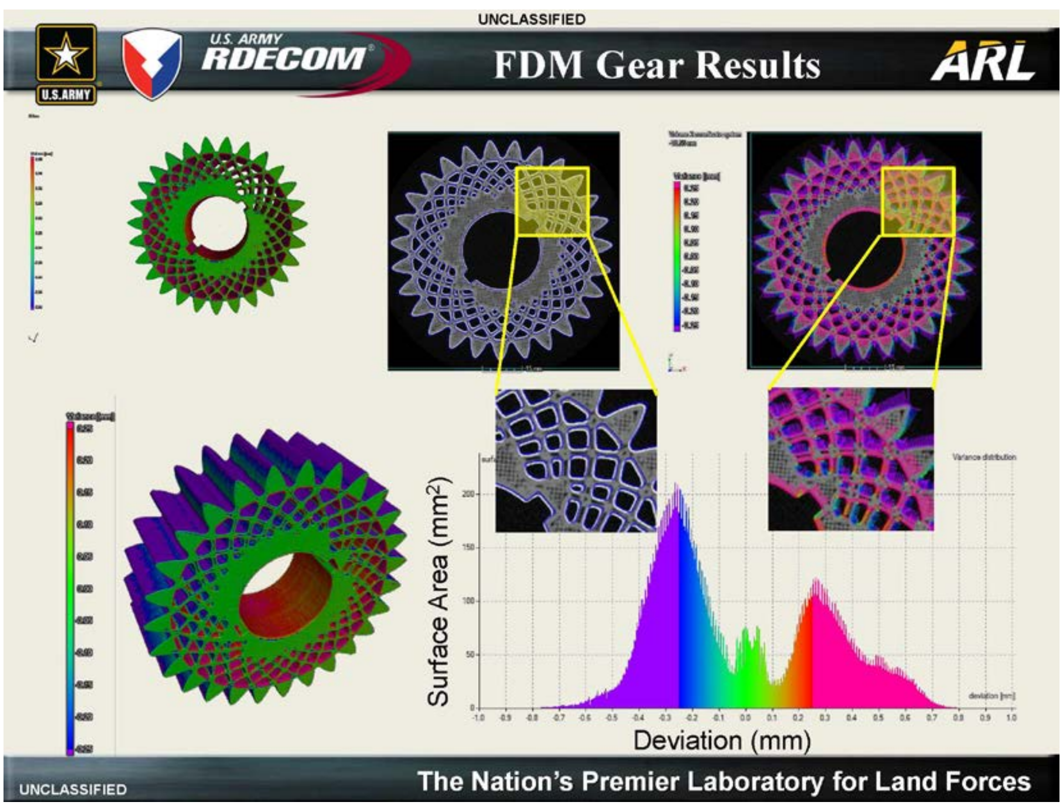

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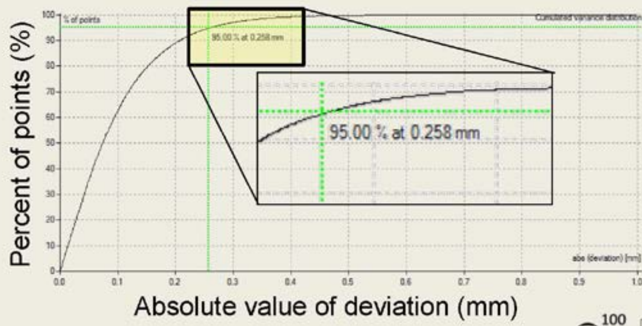
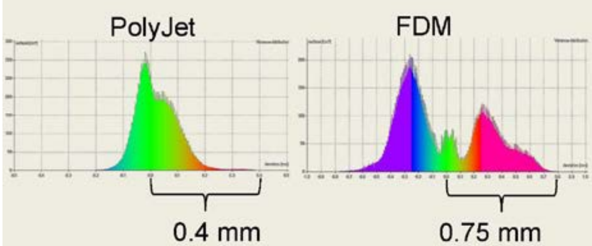
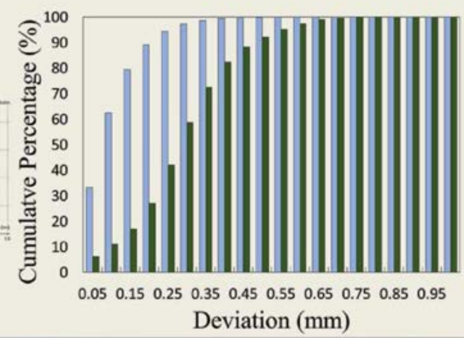
Cumulative Gear Results



Percentage	PolyJet	FDM
90	0.207	0.469
95	0.258	0.548
99	0.368	0.651





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Analysis Example 1:
Nominal/Actual Comparison

Analysis Example 2:
Porosity Quantification

Analysis Example 3:
In-Situ Mechanical Testing

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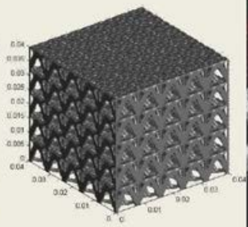
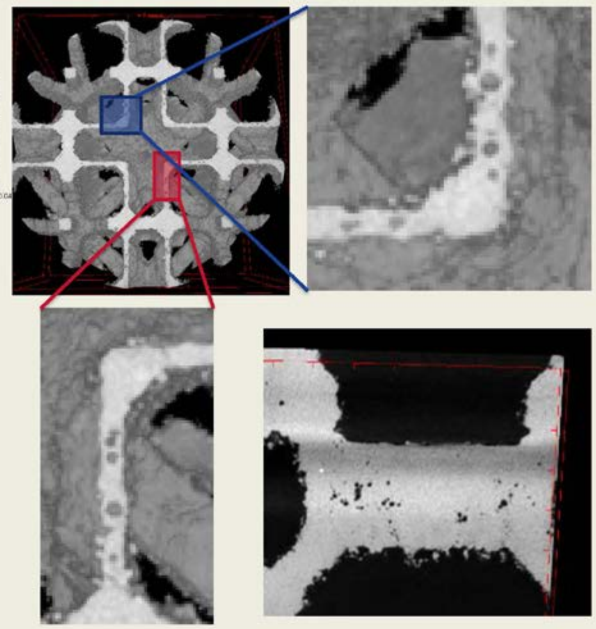
Al Truss Results

ARL

- **Scan 1:** 56.6 um voxel size (to fit entire 40 x 40 x 40 mm part)
- **Scan 2:** 14.8 um voxel size (higher resolution to view internal voids and surface roughness)





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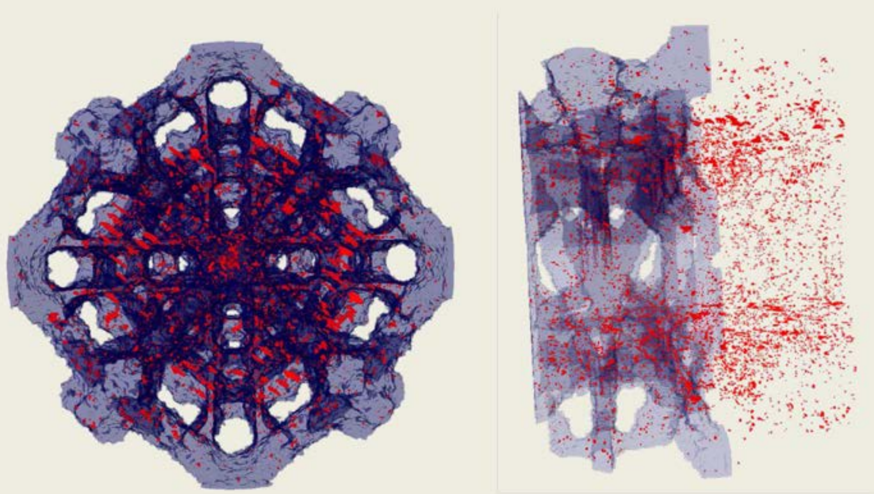
Segmentation of Internal Voids

ARL



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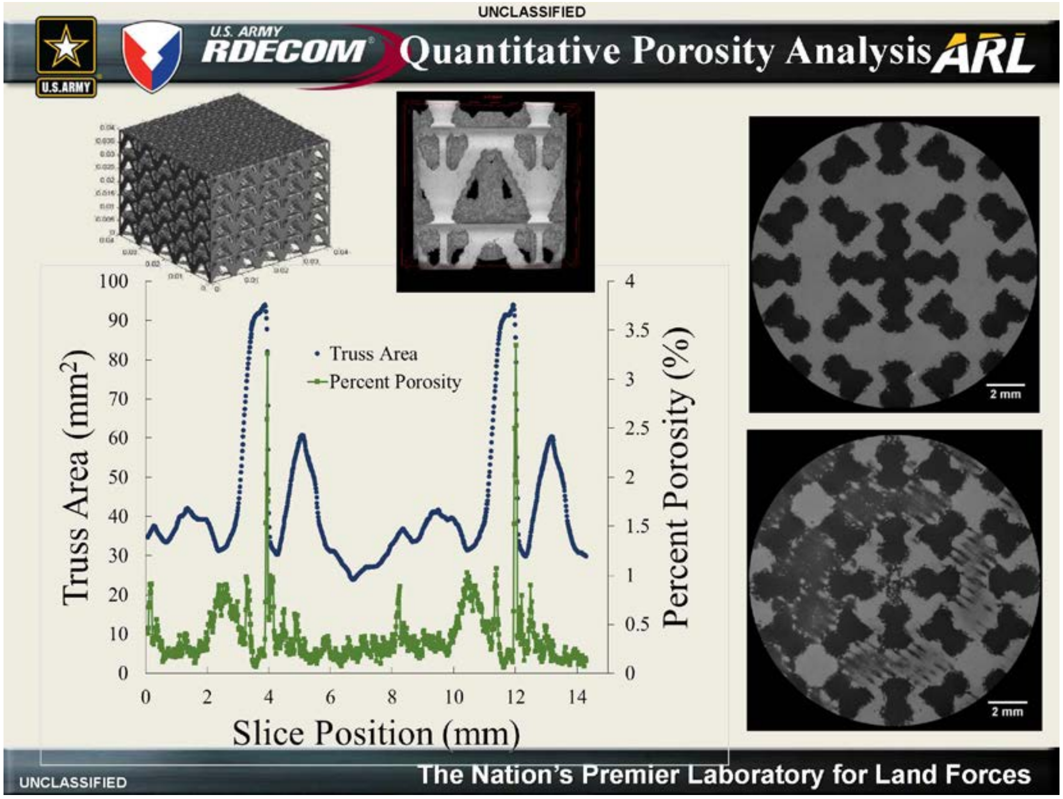

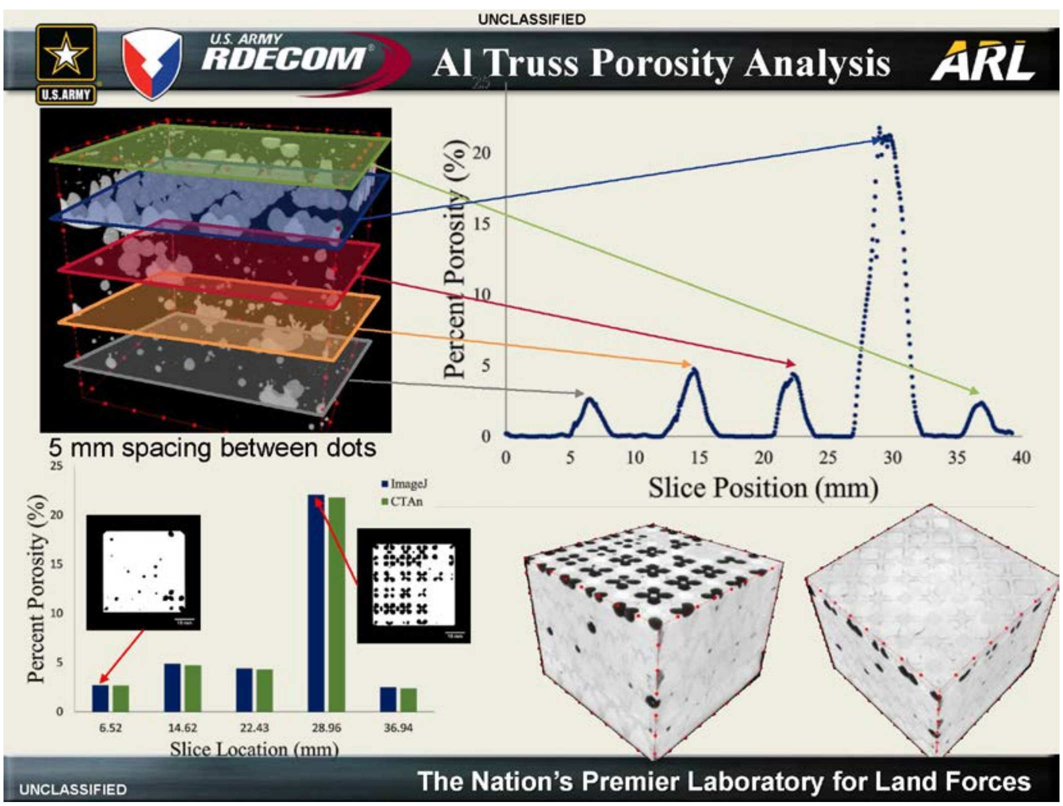

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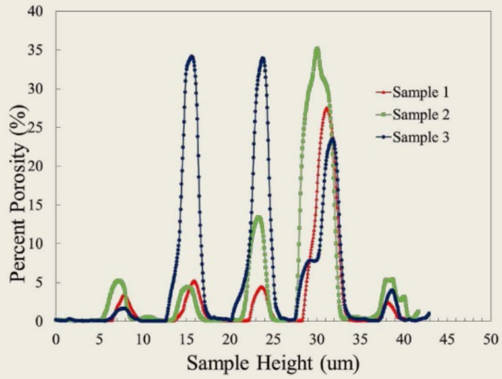

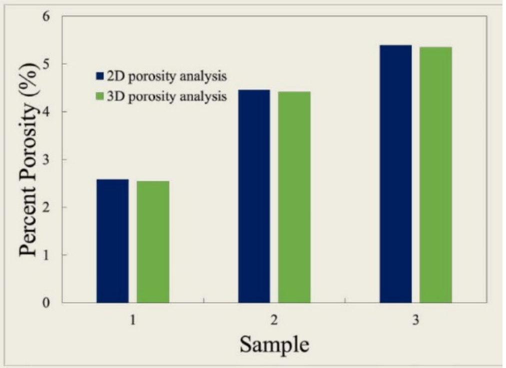

- There are clear regions where there are problems infiltrating the truss structure
  - Truss repeats unit cells every 8 mm which corresponds to the spacing between local maximums
- Overall percent porosity ranges from 2.6% to 5.4%
- 2D and 3D quantification methods are in close agreement

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Analysis Example 1:
Nominal/Actual Comparison

Analysis Example 2:
Porosity Quantification

Analysis Example 3:
In-Situ Mechanical Testing

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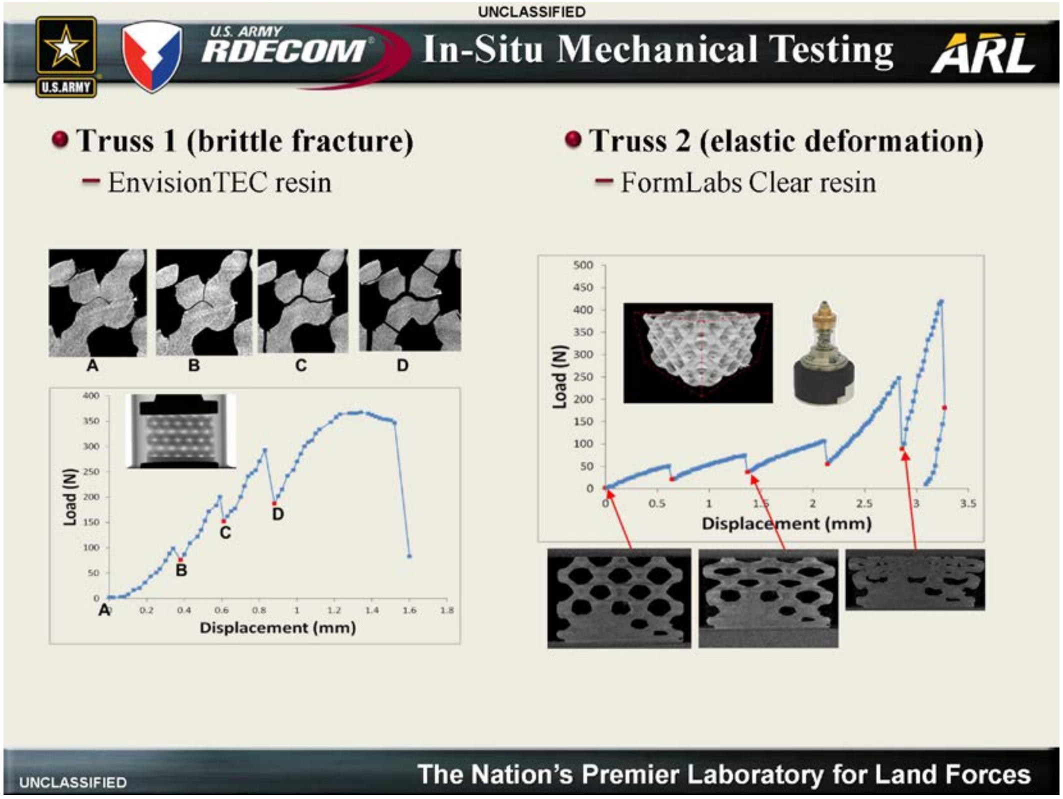

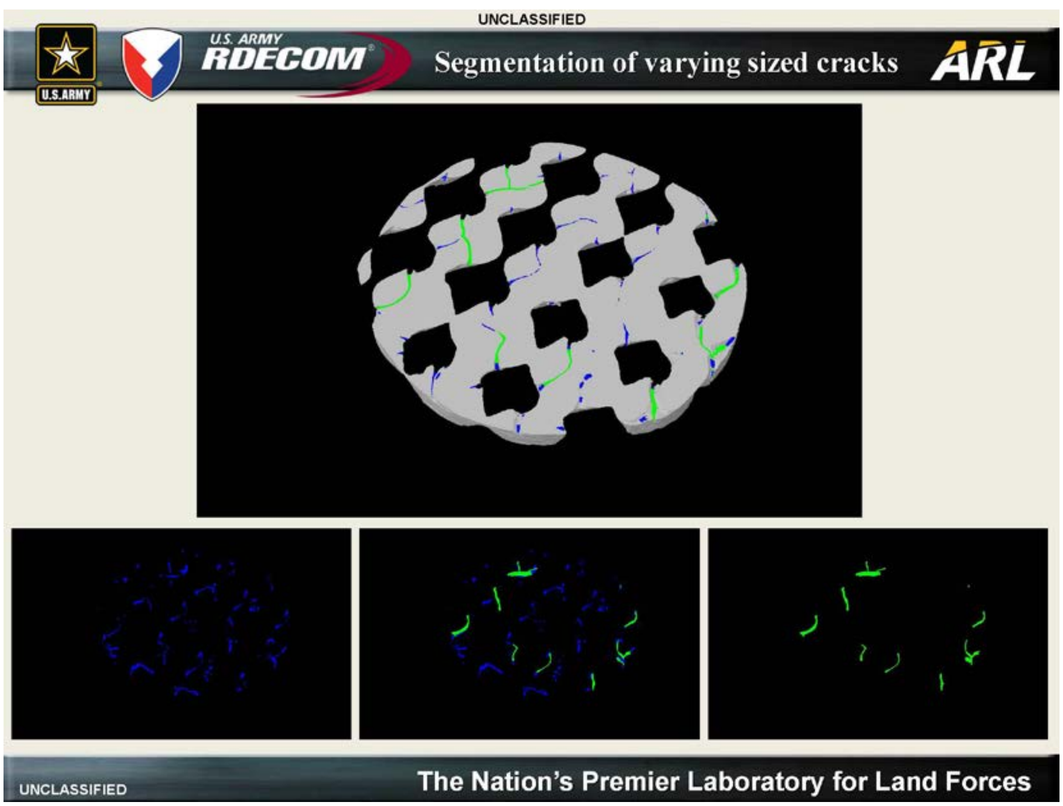

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Conclusions

ARL

- X-ray Computed Tomography is a valuable technique for 3D, non-destructive evaluation of additively manufactured parts
- Tolerance differences between the designed and manufactured parts were determined for two different processing methods
- The percent porosity and location dependence of voids can be readily quantified
- In-situ mechanical tests can be conducted on stiff or elastic structures to provide insight regarding the fracture and/or deformation response
- Internal porosity or cracks or various sizes can be segmented using bitwise operations

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Acknowledgements

ARL

- **ARL**
  - Marc Pepi
  - Ray Wildman
  - Bill Green
  - Andy Gaynor
- **Penn State ARL: Manufacturing of metal truss**
- **Rutgers University: Prof. Riman**

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5. Quality Assurance Methods for Additive Manufacturing Processes: Motivation, Challenges, and Opportunities

Jonathan Miller
(Air Force Research Laboratory/Metals Branch)

There has been significant work to date in the metal powder bed fusion community focused on understanding the influence of global processing parameters on microstructure and defect content (e.g., beam speed, power, spot size). However, a range of other implicit details are important, though they are not necessarily simply described. The present work focuses on the development of a novel technique to assess the impact of the energy input process details on material quality. This requires transformation of both in-situ process monitoring data and build-intent information into a voxelized representation, subsequent fusion with postbuild X-ray computed tomography measurements, and analysis to identify correlations between processing details and structure. An example case generated in laser powder bed fusion of Ti-6Al-4V demonstrates this process by identifying correlations between location-specific processing details and porosity.

Quality Assurance Methods for Additive Manufacturing Processes: Motivation, Challenges and Opportunities

MFPT 2016
24 May 2016

Jonathan Miller,
Edwin Schwalbach, Michael Groeber
Air Force Research Laboratory,
Materials & Manufacturing Directorate

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Talk Outline

- Metal Powder Bed AM Process Explanation
- Quality Assurance Methods
  - Post-Build Methods
  - In-Situ Methods
- Data Fusion & Analytical Tools

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Motivation

- Additive Manufacturing is "a process of joining materials to make objects from 3D model data, usually layer upon layer" – ASTM F2792
- *Potential* benefits include:
  – Rapid turn-around & short lead times
  – Extended geometric complexity
  – Ability to control *local* processing state
- *However*
  – Immature understanding of *Process – Structure – Property* links
  – As a result: AM design practices & process specs. lacking or non-existent

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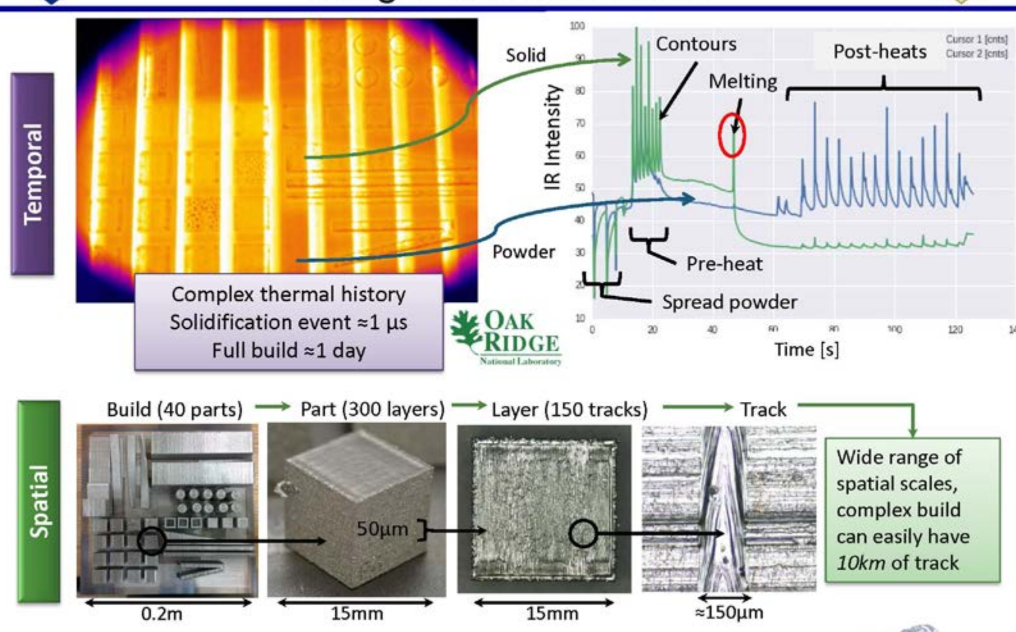
AFRL 3

Process Complexity
Length & Time Scales



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AFRL 4

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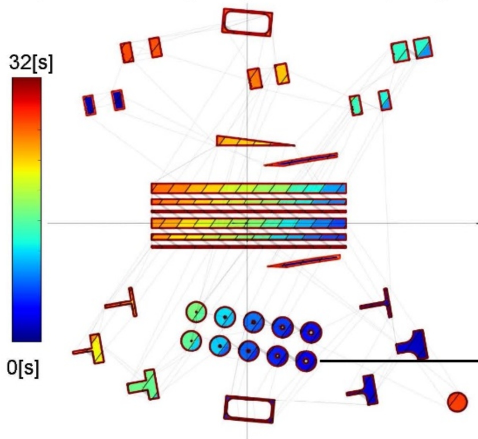
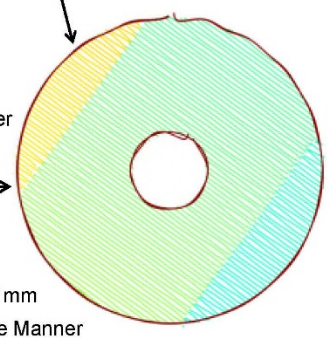
Process Complexity
Tool Path & Interpass Temperature

Path plan for a single layer colored by elapsed time





Direct Metal Laser Sintering (DMLS)
EOS M280 Machine
Striping & Hatching Enabled
Stripes Rotate 67° Per Layer

Stripes Typically 1s-10s of mm
Stripes Processed in Serpentine Manner
Laser Moves ~1 m/s
Laser Crosses Stripe in ~1/200 s

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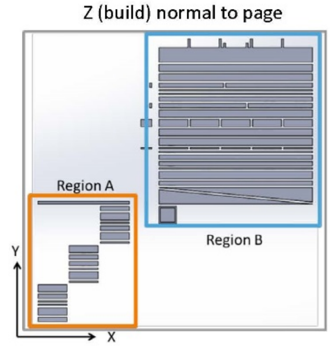
AFRL 5

Process Complexity
Geometry Variations & Process Changes

Arcam A2 e-beam powder bed fusion: Ti-6Al-4V

- Notional parameters uniform throughout bed
- Local processing parameters changed by system in response to geometry
- 3D maps of processing parameters generated via ORNL code

Z (build) normal to page



Conditions/Parameters (Normalized to Region A)

	Region A	Region B
Length [mm]	20	107.6
Power/P_A	1	4.67
Spot Velocity/V_A	1	8.10
Line Velocity/V_A	1	1.5
Scan time/t_A	1	0.636
Energy density/E_A	1	0.556

Property variations observed with…
- Different orientations (build direction debits)
- Thicknesses within a “Region” (1-5 mm)
- “Region A” to “Region B” (machine algorithm)
- Powder Lot Variations & Recycle Strategies
- Machine S/Ns, Machine Models, Vendors

…not to even count process knob changes…

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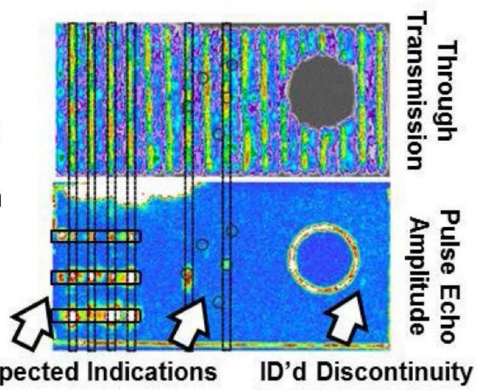
AFRL 6

Talk Outline

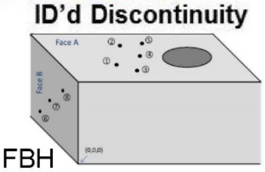
- Metal Powder Bed AM Process Explanation
- Quality Assurance Methods
  - Post-Build Methods
  - In-Situ Methods
- Data Fusion & Analytical Tools

Quality Assurance Methods
Conventional Approaches

Surface Inspection
- As-deposited porous surface finish reduces inspection effectiveness
- Fluorescent Penetrant: High background fluorescence and false positives
- Ultrasonics: Poor coupling of sound from coarse and non-planar surfaces



Volumetric Inspection (Ultrasonic)
- EBAM of Ti-6Al-4V with Beta Anneal heat treat
- Results in coarse and columnar microstructure
- Limits effective inspection depth to < 1 inch to detect 3/64” D FBH
- Result: UT inadequate for some AM material-process-component configurations



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Quality Assurance Methods
Computed Tomography

Volumetric Inspection (CT)

- Post-manufacturing inspection is an integral component of quality assurance
- Conventional inspection methods are inadequate: surface and volumetric requirements
- Computed Tomography likely viable approach but lacks standardization and validation
- Assisted Defect Recognition tools inadequate: unstandardized and highly variable

FDM Structure

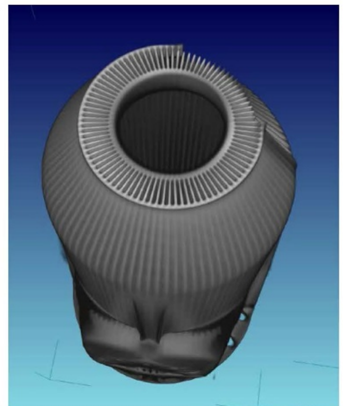
[redacted]

Thick-Thin Transitions

Fine, Distributed Porosity

[redacted]

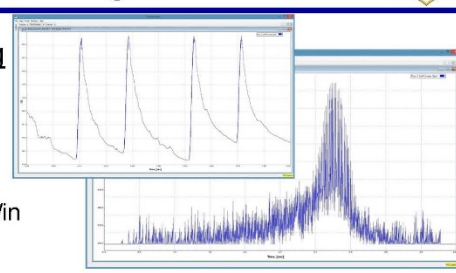
Fine Features: x-ray Scattering



Quality Assurance Methods
In-Situ Monitoring

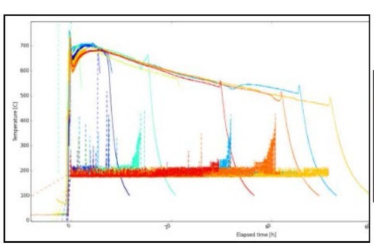
In-Process Inspection / In-Situ Monitoring

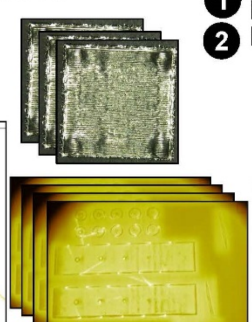
- Validated tools don't exist
- Data-intensive tools
  - Single location probes, @50kHz: 1+TB/in
  - Time resolved IR videos, @100Hz: 500GB/in
  - HD images per layer
  - Execution log files & environment
- Process interferences
- Need analytical tools

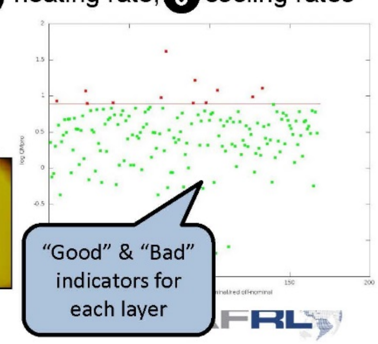


1 peak temperature

2 heating rate, 3 cooling rates







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Talk Outline

- Metal Powder Bed AM Process Explanation
- Quality Assurance Methods
  - Post-Build Methods
  - In-Situ Methods
- Data Fusion & Analytical Tools

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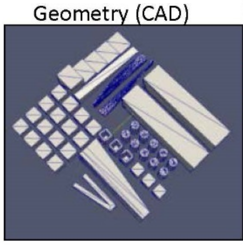
AFRL 11

Data Fusion & Analytical Tools

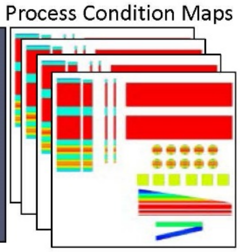
Systematic collection and analysis of planning, execution, and post build characterization data sets

Planning: process intent

Geometry (CAD)

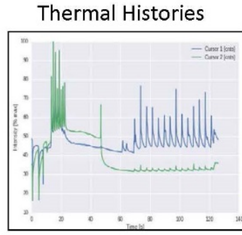


Process Condition Maps



Execution: process reality

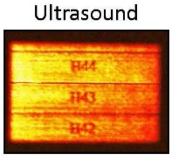
Thermal Histories



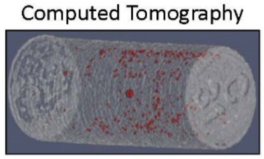
IR videos

Outcome: microstructure, defects & properties

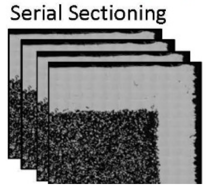
Ultrasound



Computed Tomography



Serial Sectioning



Mechanical Testing

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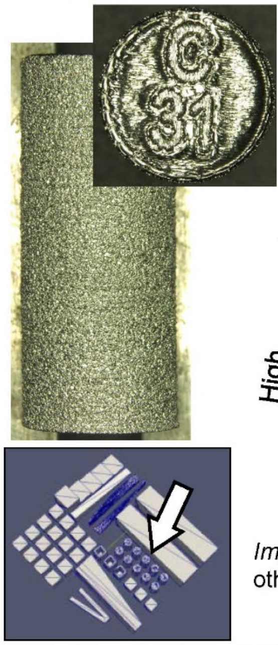
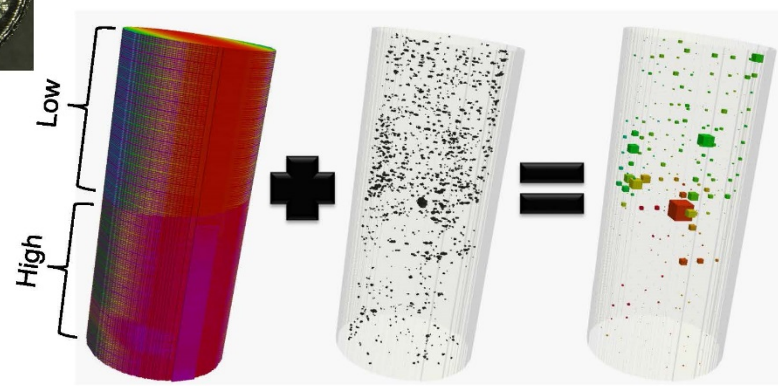
Electron Beam Melting Example
Planning & CT Data Fusion





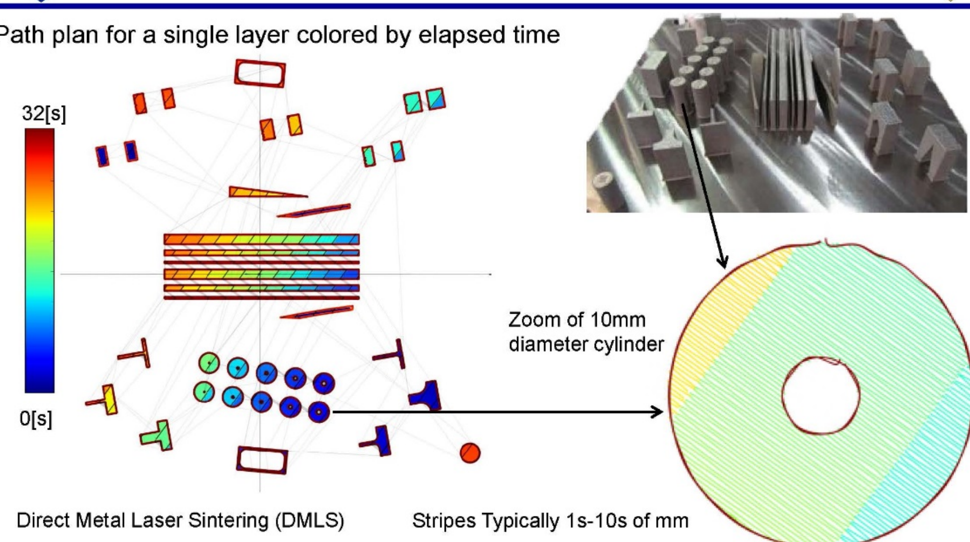
Power
Implicit change due to other parts located in bed

CT data:
Pore location, size

Size → Pore vol. frac.
Color → Average power

Laser Powder Bed Fusion Example
In-Situ & CT Data Fusion

Path plan for a single layer colored by elapsed time



Direct Metal Laser Sintering (DMLS)
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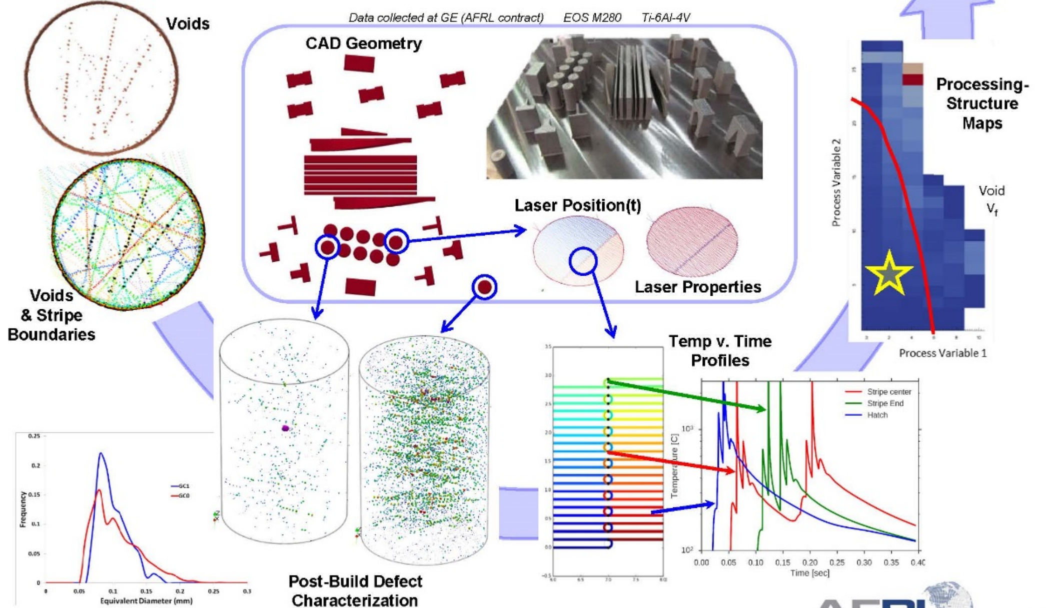
Stripes Processed in Serpentine Manner
Laser Moves ~1 m/s
Laser Crosses Stripe in ~1/200 s

Laser Powder Bed Fusion Example

In-Situ & CT Data Fusion

Control Spatial Processing Variation → Control Structure



Acknowledgements

<u>Materials &Processing Team</u>

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Norman Schehl

<u>X-ray CT</u>

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<u>ORNL Manufacturing Demo. Facility</u>

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6. Air Force Vision and Challenges for Additive Manufacturing of Functional and Soft Matter Materials

Dan Berrigan
(Air Force Research Laboratory/Metals Branch)

Flexible hybrid electronics (blending printed and places devices) is the focus of our research team at the Air Force Research Laboratory's Materials and Manufacturing Directorate. In this talk we highlight a few projects in additively manufactured electronics (e.g., batteries, capacitors, antennas) that span bench-level research to engineered solutions. In addition, we will discuss our path forward as we begin to explore the fundamental materials and processing challenges associated with pattern stimuli responsive materials and design of soft mechanical structures/ actuators.

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Additive Manufacturing for Air Force Applications

Dan Berrigan, Ph.D.

AFRL/RXAS
Materials & Manufacturing Directorate
Air Force Research Laboratory
Wright-Patterson AFB, OH 45433

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- **Giorgio Bazzan**, Researcher
- **James Hardin**, Researcher

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Air Force Research Laboratory Technical Competencies

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AFRL 3

Some Aspects of the Hype

- Additive manufacturing (AM) ***promises reduced lead time***, ***reduced cost***, ***mass customization***, ***weight reduction***, ***part consolidation*** **and** ***enhanced geometric complexity***.
- Single process lead time, cost and energy consumption advantage potentially overwhelmed by limitations in pre-AM and post-AM processes
  - Feedstock Availability & Energy
  - Machining, Heat treatment
- Breadth of AM technology across process speeds, spatial resolution, material classes, material quality and sense of "the replicator" confuses the uninitiated

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AFRL 4

Benefits and Challenges

AF Benefits:

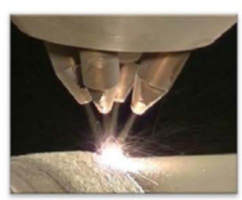
- Reduced lead time and cost for small production runs
  → Aircraft Availability & Sustainment Affordability
- Mass customization and enabling geometric complexity
  → Adaptive Warfighter & Energy Efficiency
- Weight reduction via part consolidation/material substitution
  → Reduced Sustainment Burden & Energy Efficiency

Technical Challenges:

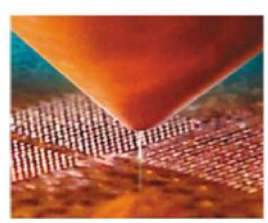
- *Unquantified material quality* with undefined inspection protocols to meet structural requirements
- *Highly variable* material properties and lack of statistical databases for design
- *Lack of standardized process controls* typically required for structural applications
- *Inadequate cost models* for representation of post-processing requirements
  - Inspection, Machining, and Heat Treatment

AFRL Additive Manufacturing Strategy

- **Quantify Risk Upon Substitution and Implementation of AM**
- **Inform the Qualification of Additive Materials and Processes**
  - Process monitoring and sensing
  - NDE and material characterization
  - AM-tailored material development
  - Component demonstration



- **Advance AM Capabilities via Modeling & Simulation**
  - Process simulation for design & control
  - Verification & Validation for qualification
  - Process-structure-property relationships
  - Develop digital thread for AM components



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Staged Implementation Potential of AM
An AFRL/RX Perspective

Now…
- early design prototypes
- process implements (fixtures, tooling)
- polymeric applications (ducting, brackets)

Soon…
- niche AM applications
- reduced-life or 'safe-life' components
- 'attritable' applications (RPVs, munitions)

Later…
- full-life, non-critical structural applications
- embedded electronics/sensors

Far-Term…
- fracture-critical hardware …?
- hybrids and graded materials …?

How to Shortcut the Timeline
- Design for AM
- Quantify Risk
- Quantify Mfg Variability
- Develop Cost Models

What are "niche AM apps"?
- Component Redesign
- Complex Geometry
- Non-critical Hardware
- Small Lot Production
- Short Life Applications

Process Maturity →

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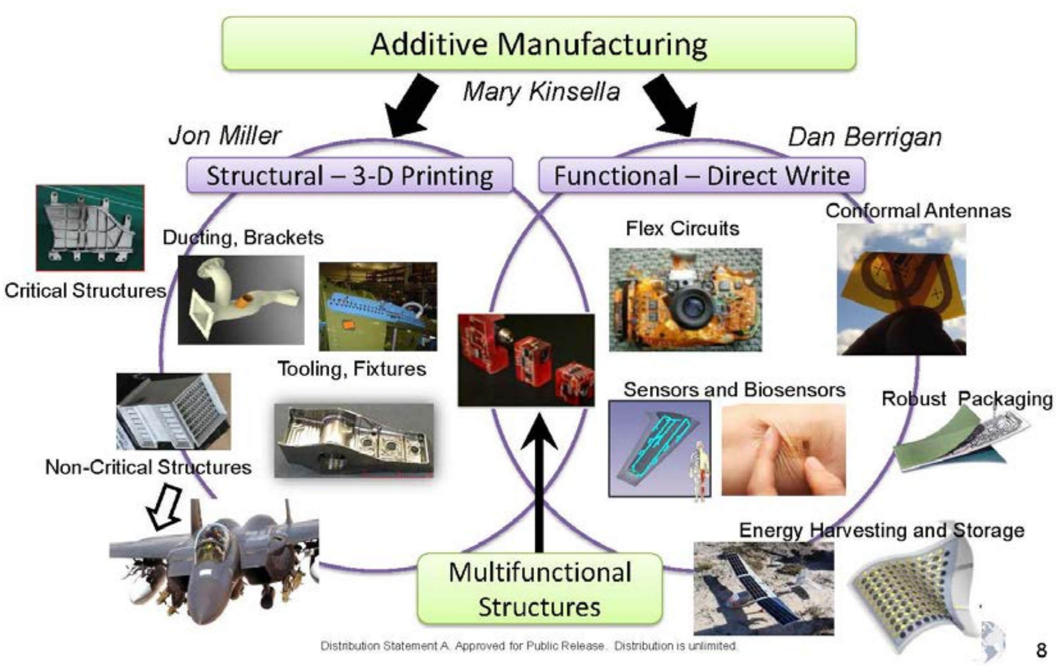
AFRL 7

Structure vs. Function
…and the opportunities in between



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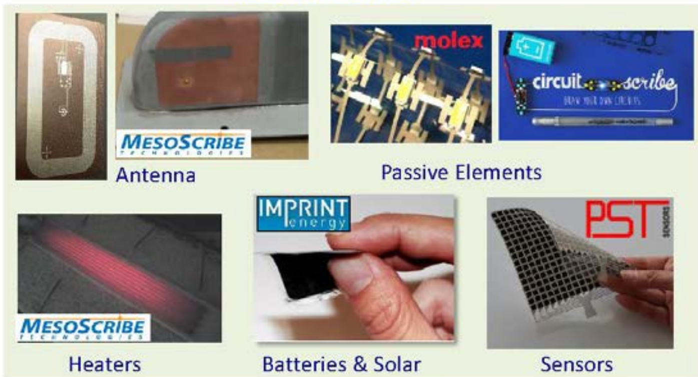
Flex Hybrid Concept

Print what you can, ***place what you can't***

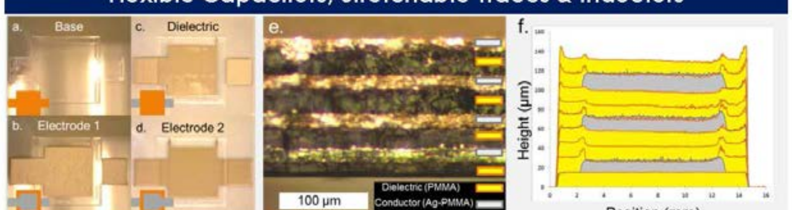
Printed Electronics



Placed Electronics

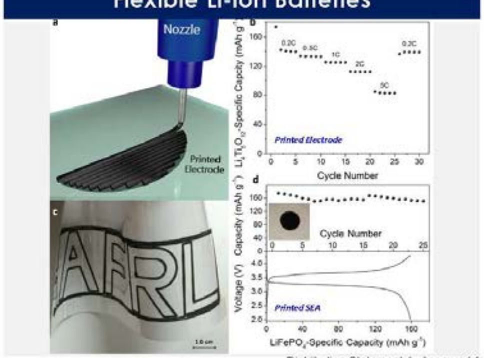
Fully Printed Devices

Flexible Capacitors, Stretchable Traces & Inductors



Hardin, Berrigan

Flexible Li-Ion Batteries



Kohlmeyer, Blake, Hardin, Durstock

Conformal Antennas

Leever, Berrigan, Theodore, Durstock

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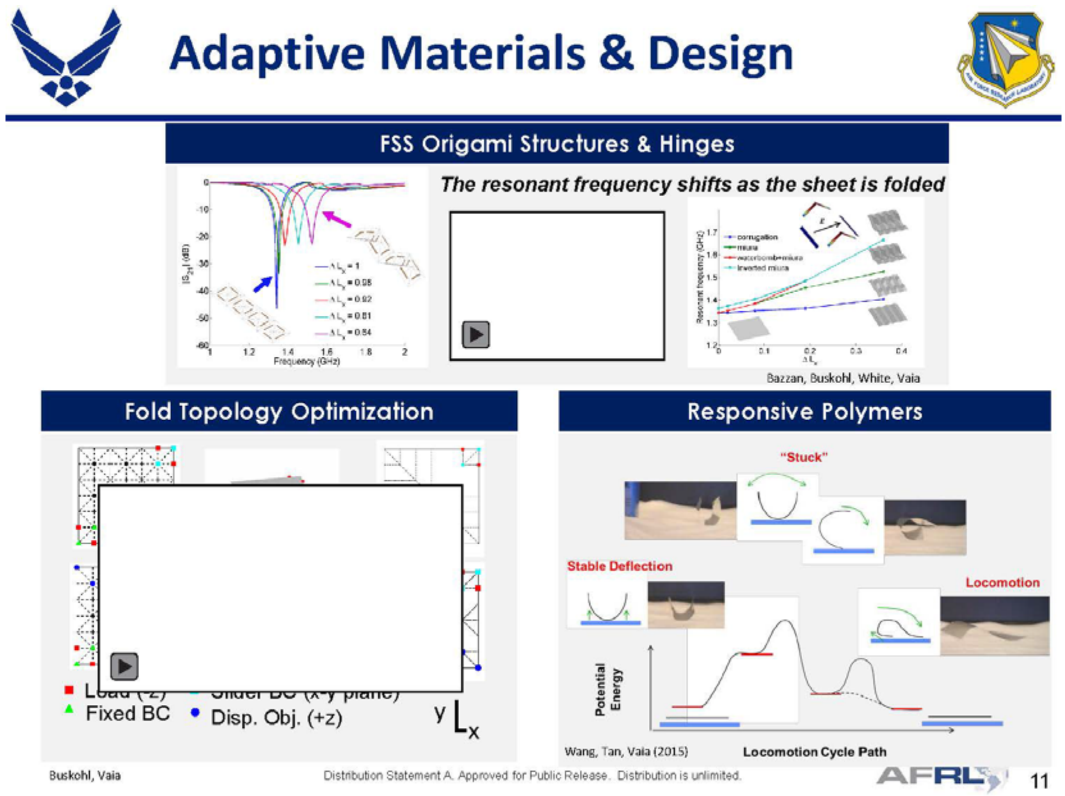

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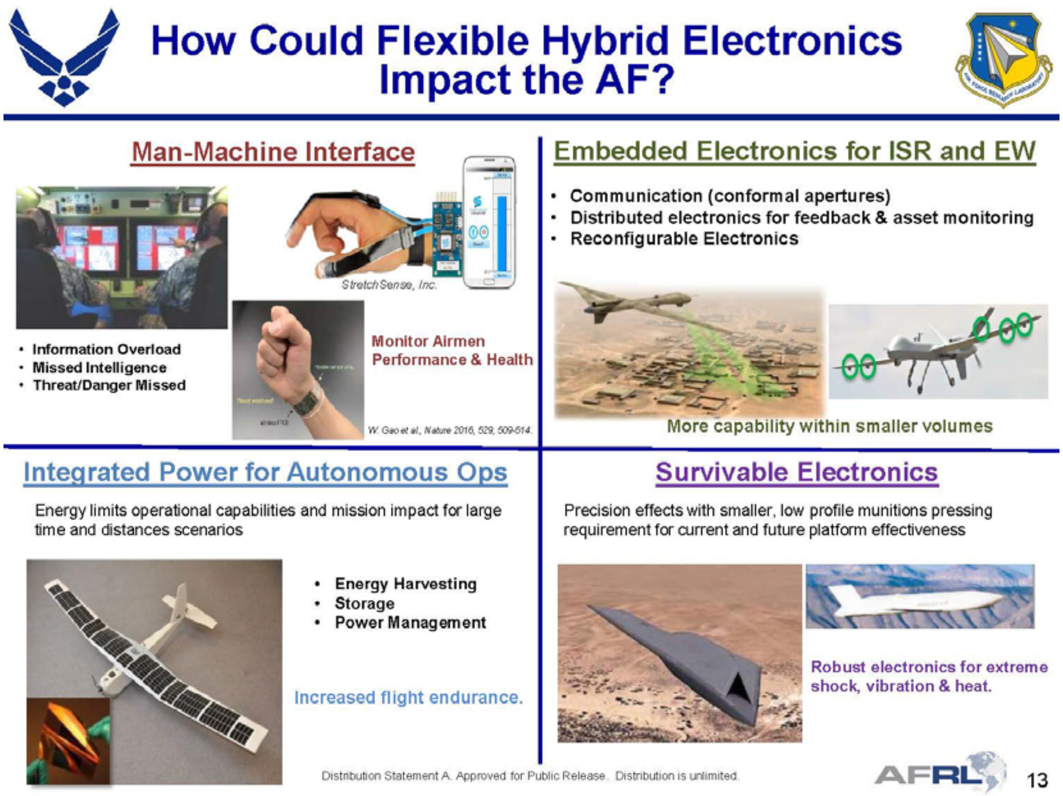
How Could Flexible Hybrid Electronics Impact the AF?
Man-Machine Interface
StretchSense, Inc.
• Information Overload
• Missed Intelligence
• Threat/Danger Missed
Monitor Airmen Performance & Health
W. Gao et al., Nature 2016, 529, 509-514.
Embedded Electronics for ISR and EW
• Communication (conformal apertures)
• Distributed electronics for feedback & asset monitoring
• Reconfigurable Electronics
More capability within smaller volumes
Integrated Power for Autonomous Ops
Energy limits operational capabilities and mission impact for large time and distances scenarios
• Energy Harvesting
• Storage
• Power Management
Increased flight endurance.
Survivable Electronics
Precision effects with smaller, low profile munitions pressing requirement for current and future platform effectiveness
Robust electronics for extreme shock, vibration & heat.
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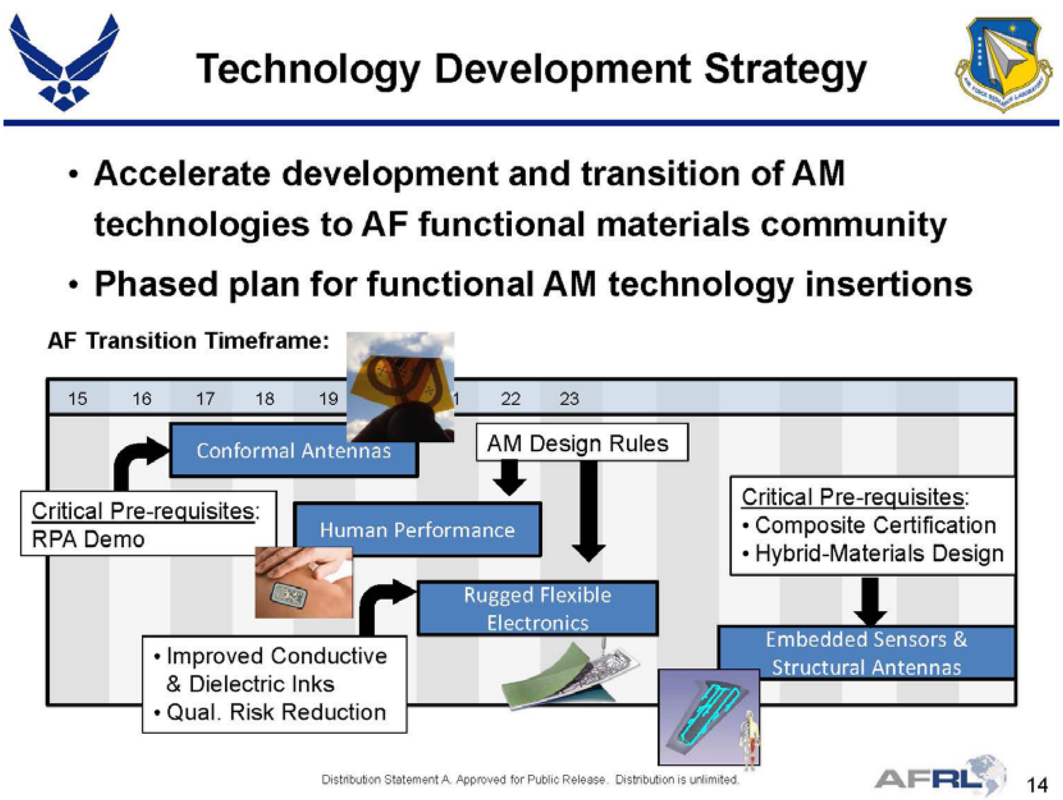
Technology Development Strategy
• Accelerate development and transition of AM technologies to AF functional materials community
• Phased plan for functional AM technology insertions
AF Transition Timeframe:
15 16 17 18 19 1 22 23
Conformal Antennas
AM Design Rules
Critical Pre-requisites:
RPA Demo
Human Performance
Critical Pre-requisites:
• Composite Certification
• Hybrid-Materials Design
Rugged Flexible Electronics
Embedded Sensors & Structural Antennas
• Improved Conductive & Dielectric Inks
• Qual. Risk Reduction
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Summary

- **AF pursuing additive manufacturing to enable numerous capabilities including**
  - Human/airman performance monitoring
  - Rugged/durable electronics
  - Embedded electronics & optics
- **Flexible Hybrid Electronics (rather than fully printed solutions) are near-term focus**
  - In-house R&D
  - External efforts with universities and industry
  - Leveraging NBMC, America Makes, and NextFlex
- **Key Challenges**
  - Ink development – both metals & dielectrics
  - Process enhancements – in-situ process monitoring, improved resolution, etc.
  - Multi-material print heads or print systems

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7. Army Research Laboratory's Additive Manufacturing for the Future Expeditionary Force

Ricardo Rodriguez
(Army Research Laboratory, Weapons and Materials Research Directorate)

One major Army focus is in converting our traditional force into a more expeditionary force. This will result in severe reductions in the logistics tail but will require Army forces to become more adaptive. Units, equipment, and personnel will need to be configurable and reconfigurable based on mission parameters. To accomplish this, the Army will be conducting more in-field, or point-of-need, manufacturing than ever before. Other areas of concentration include man-machine interface, capabilities organic to the Warfighter, unmanned systems, networks, and robotics. Many of the materials and technologies needed to accomplish these goals are still experimental, if they exist at all. This presentation will cover the Army Research Laboratory's Additive Manufacturing activities and discuss several research topics that will allow for the success of this future expeditionary force.

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Advanced Manufacturing Research & Development
MFPT – Additive Manufacturing Session
Dayton, OH - 5/24/16
Larry R. Holmes, Jr. (ARL)
larry.r.holmes.civ@mail.mil
Ricardo X. Rodriguez (SURVICE Eng.)
ricardo.x.rodriguez4.ctr@mail.mil
Weapons and Materials Research Directorate
Materials and Manufacturing Sciences Division
Manufacturing Sciences and Technology Branch
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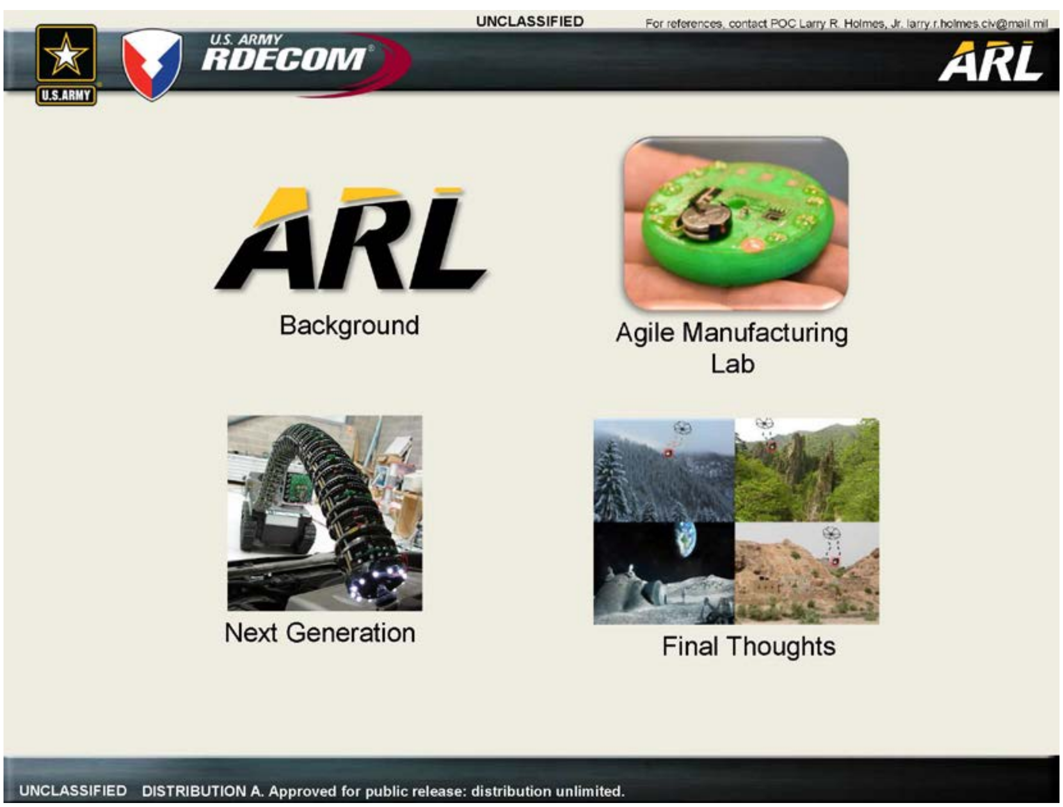
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Agile Manufacturing Lab
Next Generation
Final Thoughts
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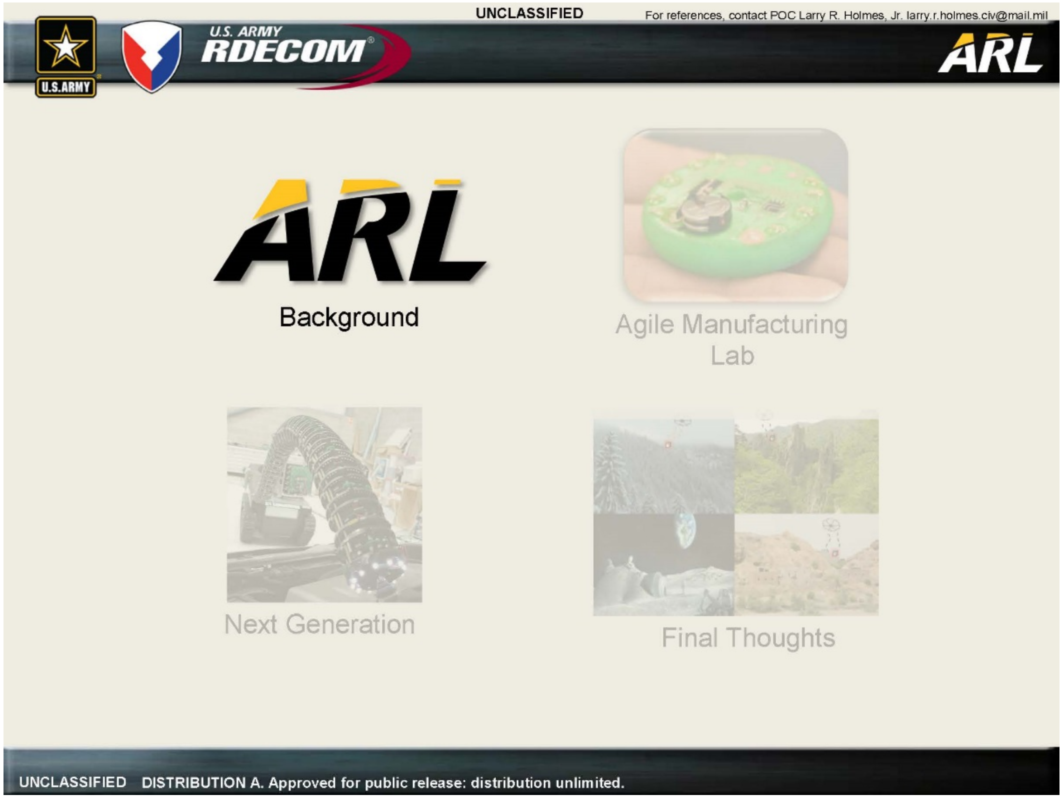
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Final Thoughts
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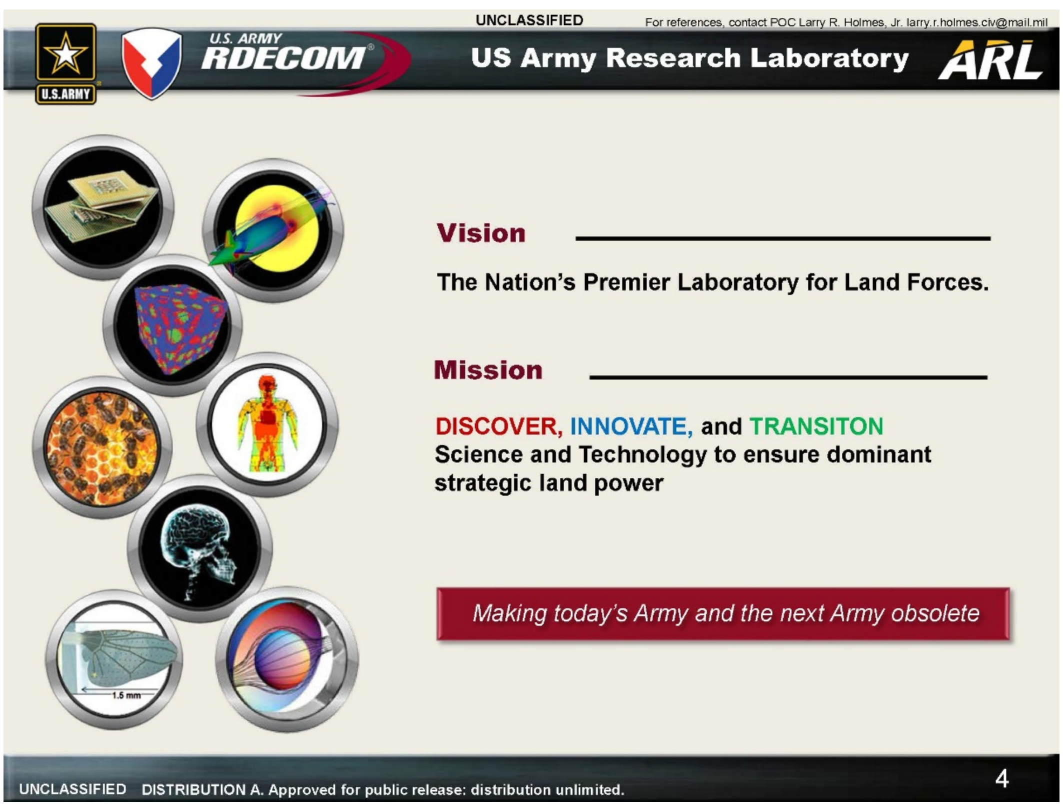
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US Army Research Laboratory
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Vision
The Nation's Premier Laboratory for Land Forces.
Mission
DISCOVER, INNOVATE, and TRANSITON Science and Technology to ensure dominant strategic land power
Making today's Army and the next Army obsolete
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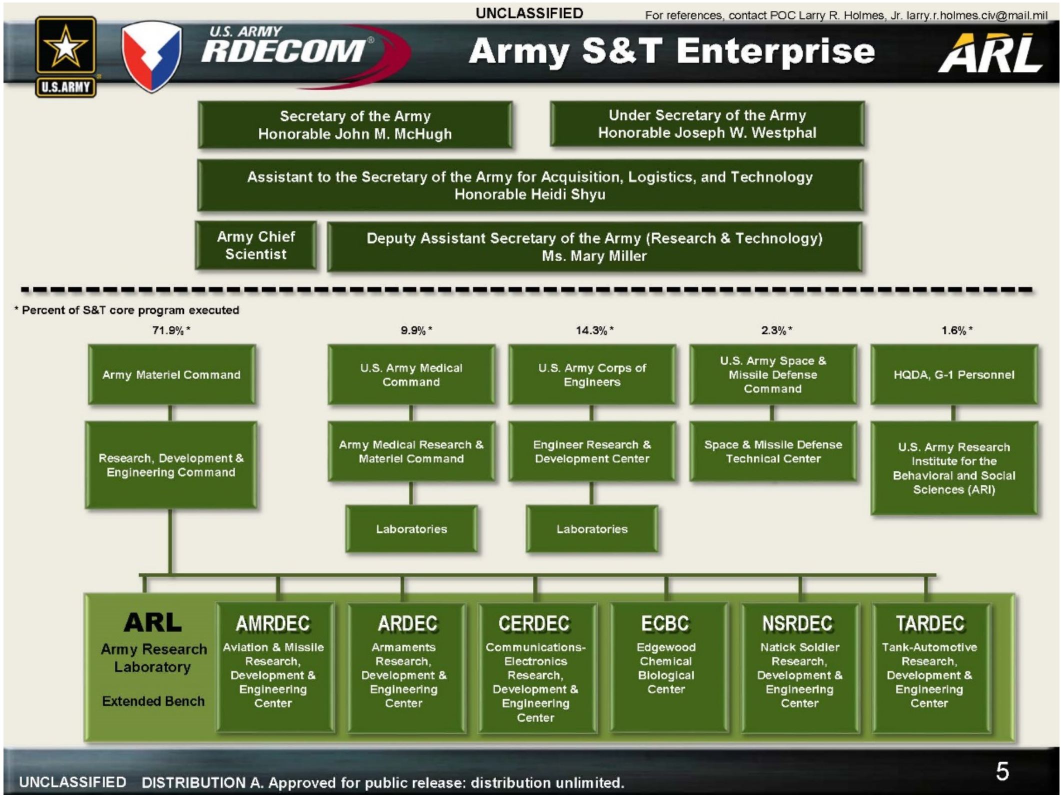

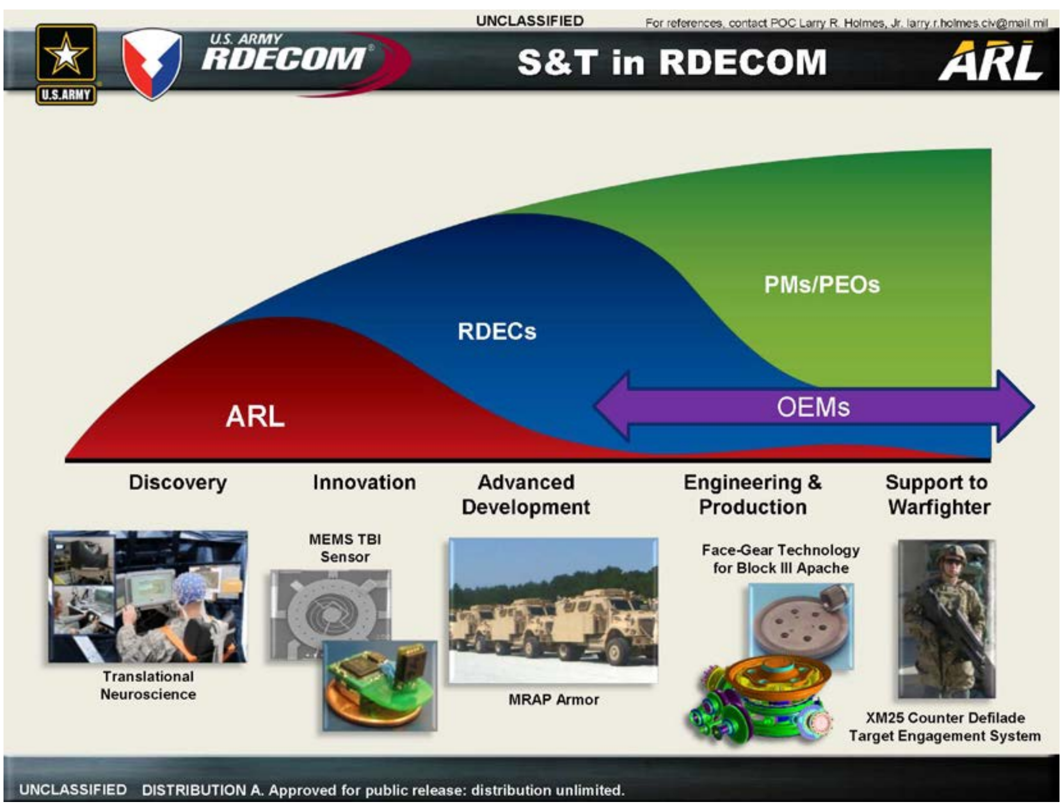

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Human Sciences
Fundamental understanding of Warfighter performance enhancement, training aids, and man-machine integration.
Information Sciences
Fundamental understanding of information generation, collection, assurance, distribution, and exploitation.
Sciences for Lethality & Protection
Fundamental understanding of emerging technologies that support weapon systems, protection systems, and injury mechanisms affecting the Warfighter
Sciences for Maneuver
Fundamental understanding of the design, integration, control, and exploitation of highly adaptive platforms in complex environments
Extramural Basic Research
Steering and oversight of the systematic study to increase fundamental knowledge and understanding in physical, engineering, environmental, and life sciences related to long-term national security needs.
Computational Sciences
Fundamental understanding of computer hardware, high efficiency algorithms, and novel mathematical methods.
Materials Research
Fundamental understanding of structural, electronic, photonic, and energy materials & devices.
Assessment and Analysis
Quantitatively Assess the development and application of analytical tools and methodologies to quantitatively assess the military utility of Army, DoD, and select foreign combat systems.
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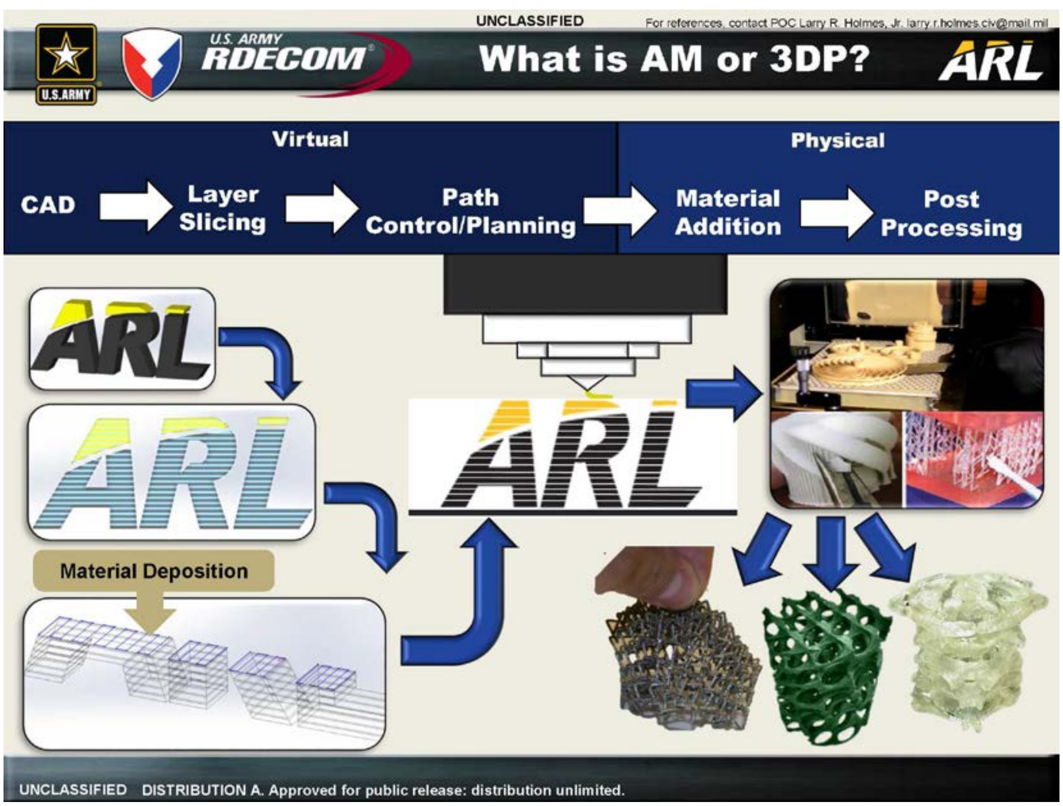
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What is AM or 3DP?
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Virtual
Physical
CAD
Layer Slicing
Path Control/Planning
Material Addition
Post Processing
Material Deposition
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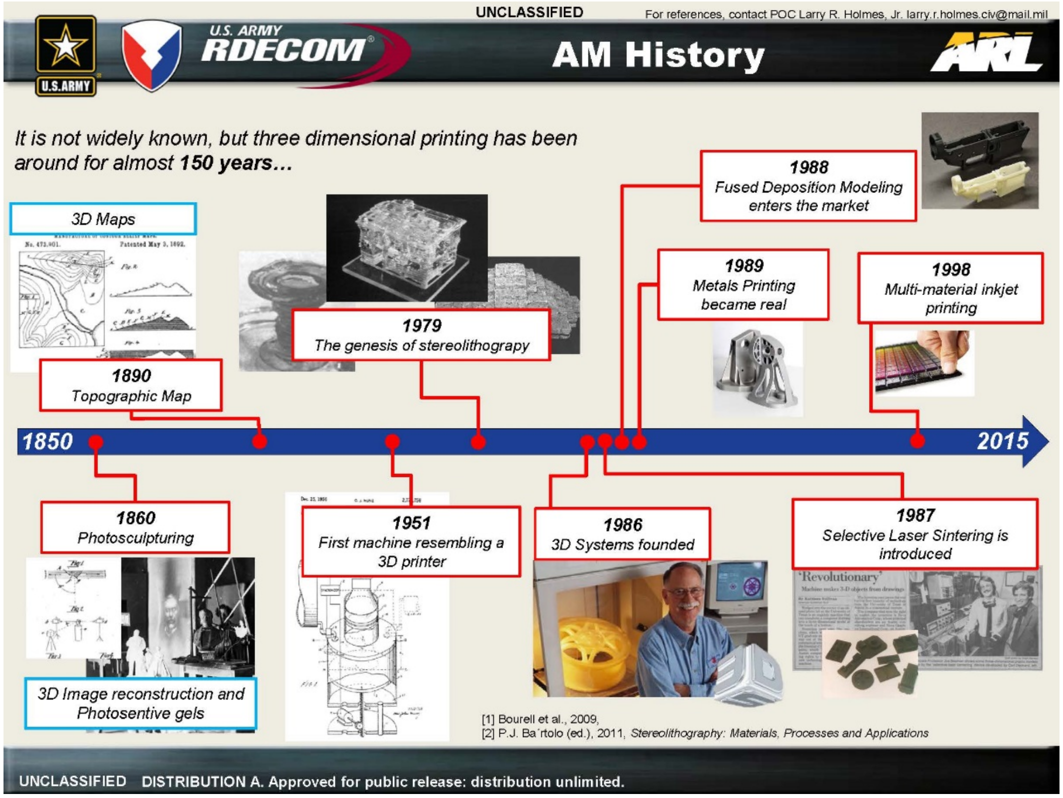
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AM History
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It is not widely known, but three dimensional printing has been around for almost **150 years…**
3D Maps
1890
Topographic Map
1979
The genesis of stereolithograpy
1988
Fused Deposition Modeling enters the market
1989
Metals Printing became real
1998
Multi-material inkjet printing
1850
2015
1860
Photosculpturing
3D Image reconstruction and Photosentive gels
1951
First machine resembling a 3D printer
1986
3D Systems founded
1987
Selective Laser Sintering is introduced
[1] Bourell et al., 2009,
[2] P.J. Ba´rtolo (ed.), 2011, Stereolithography: Materials, Processes and Applications
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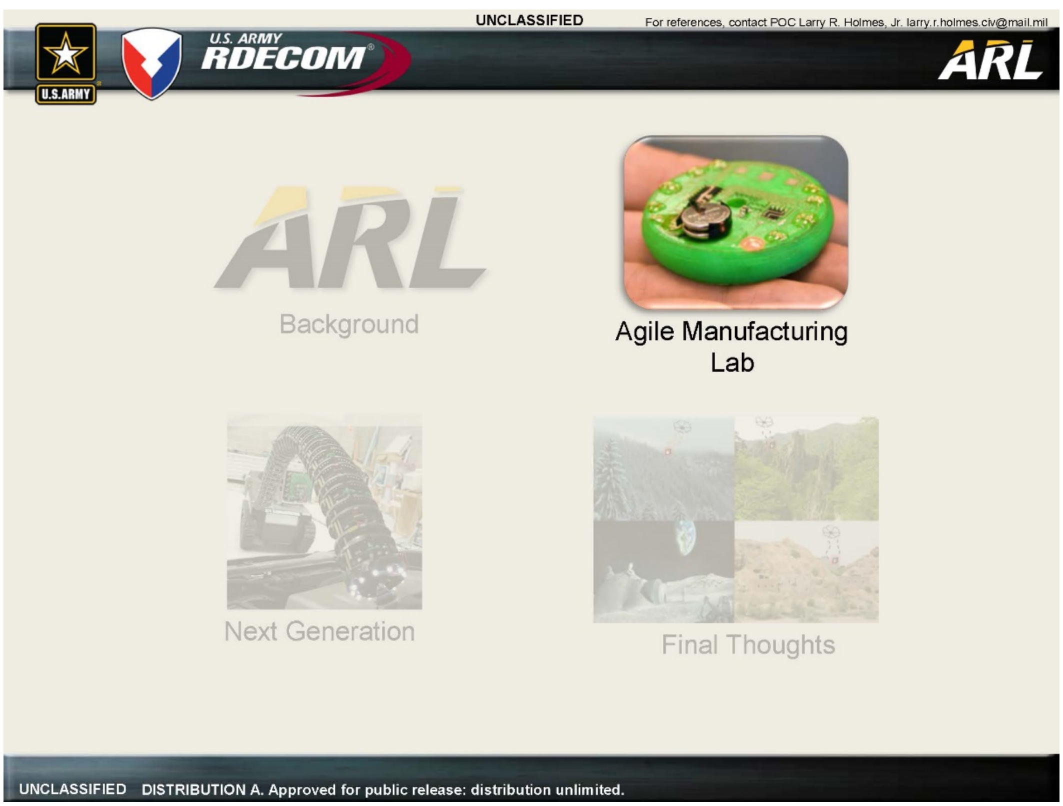
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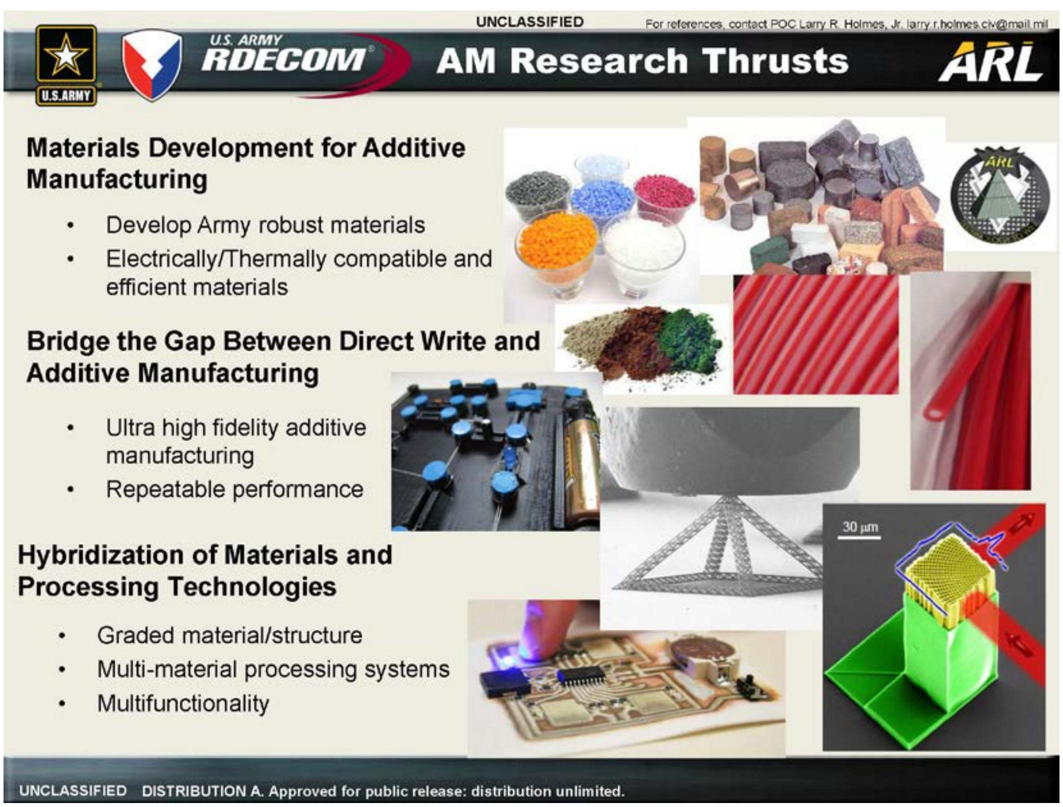

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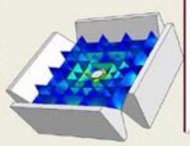
EXOD Manufacturing LAB ARL

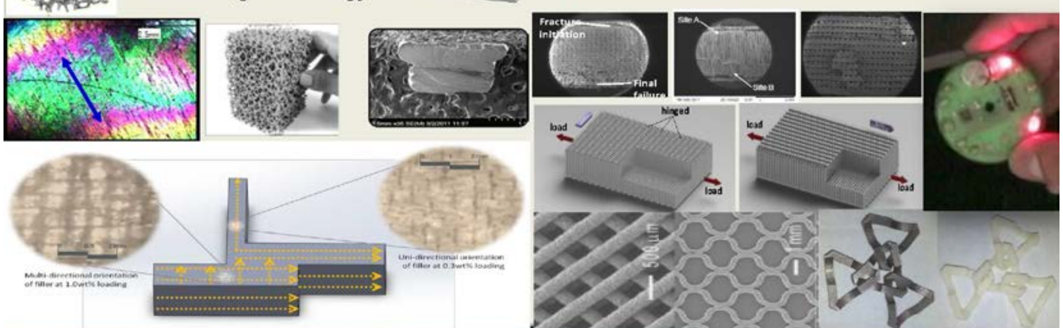
The Expeditionary On-Demand Manufacturing Lab is the Army Research Laboratory's Flagship facility for Direct Write and Additive Manufacturing Innovation.

ARL is Developing Next Level Functionality for Additive Manufacturing Technologies Through:

- **Material Development**
- **Material Multifunctionality**
- **Material Compatibility**
- **Processing Control**
- **Processing Technology**



Commercial Processes	• Polymer micro-extrusion • Micro-dispensing pump • Vat polymerization • InkJet • Aerosol jet • Cold spray • Micro-machining • Direct Metal Laser Sintering
ARL Novel/Experimental Processes	• Field-aided vat polymerization • Fiber reinforced micro-extrusion • Multi-material vat polymerization • Capillary cold spray • PRINT, a roll-on deposition • 6 axis multi-material processing • Direct Write/ AM combined



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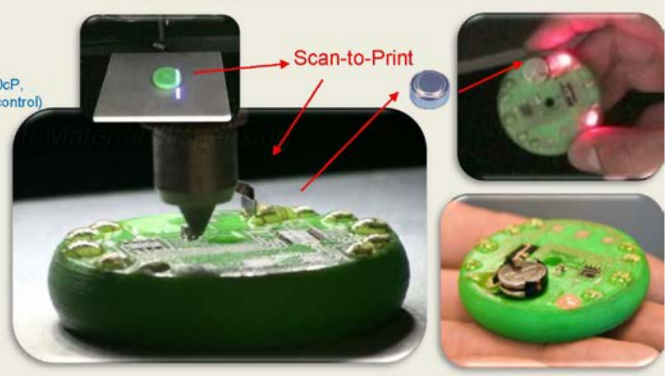
Multi-Tech AM ARL

Hybrid Manufacturing

An active example of a multi-technology printing system. The system is based on universal processing controls and software, which are fully open for manipulation (variation of processing parameters). This system includes:

- •Line Scanning
- •Thermoplastic Extrusion (up to 400°)
- •Thermoset Deposition (0 to 2,000,000cP, with pico-liter control)
- •Ink Deposition
- •6-Axis Motion Control
- •Tool Switching
- •Pick-n-Place
- •Micro-spray
- •Micro-milling
- •Laser Sintering
- •Aerosol Jet Deposition
- •Micro Cold Spray Deposition
- •Hopper and auger based feeding



With Scan-to-print capability, the SuperScrypt can deposit on complex curves, or build 3D shapes from scan data.
Inverse kinematics enabled 6-axis motion control allows for true 3D printing instead of stacking 2D layers. Robust hardware allows for +/- 200nm precision.

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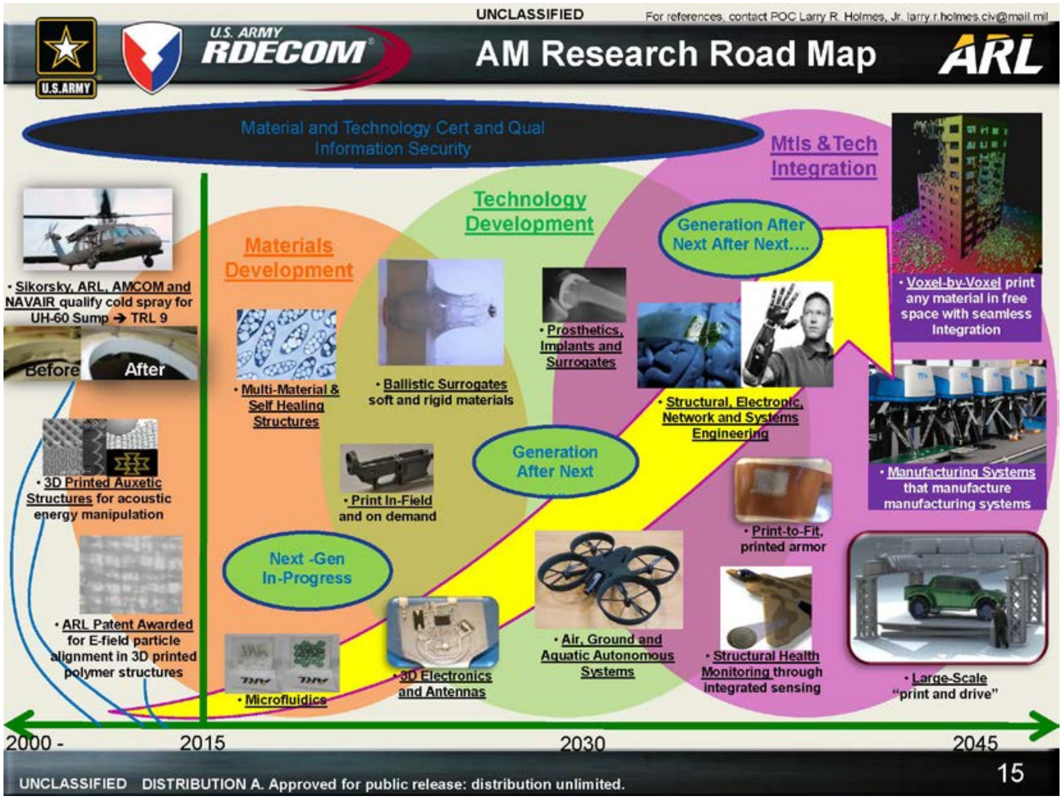

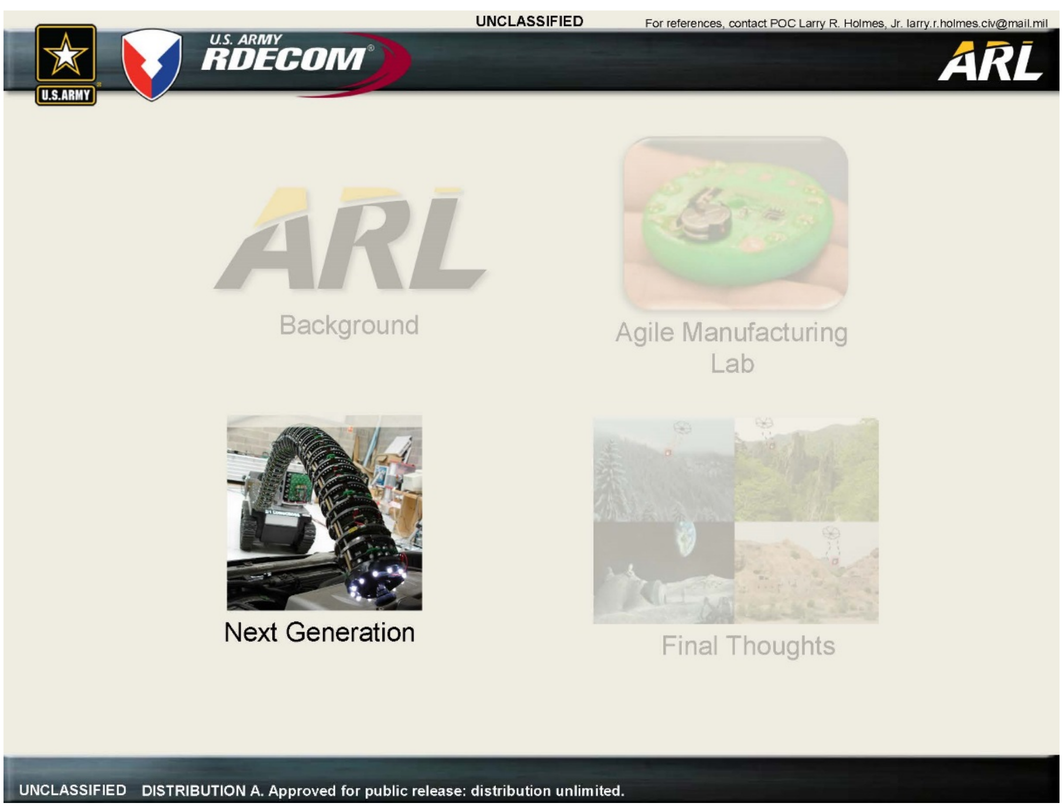

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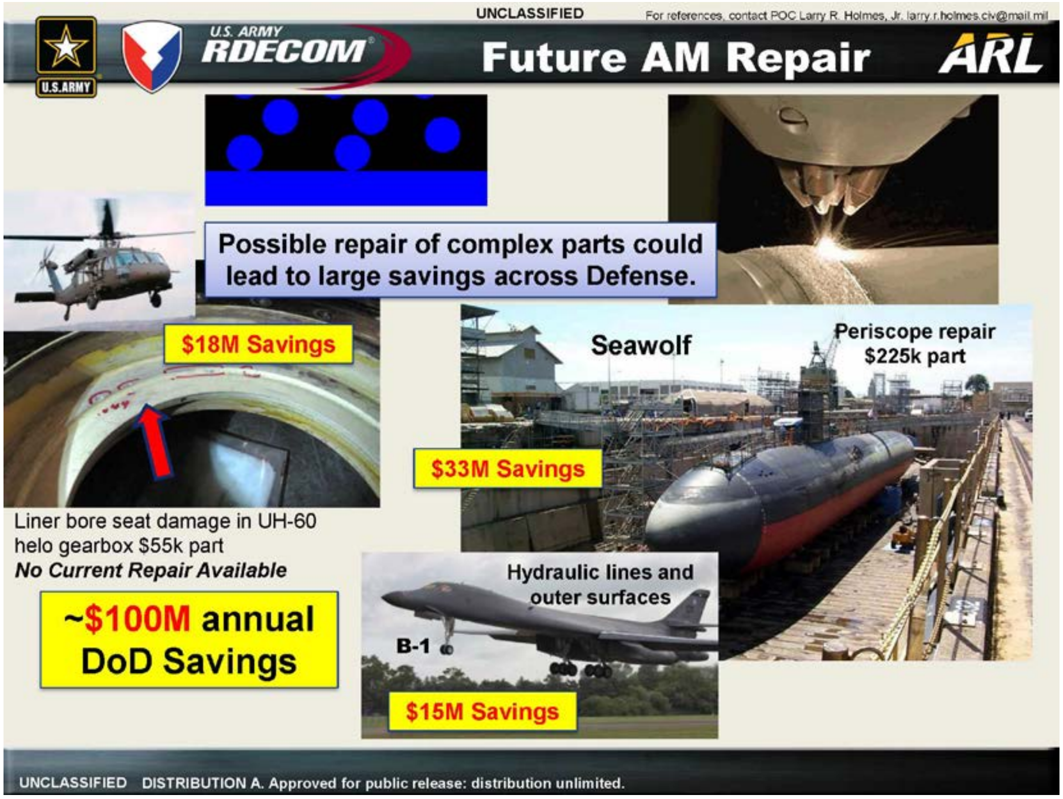
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Future AM Repair
ARL
Possible repair of complex parts could lead to large savings across Defense.
$18M Savings
Seawolf
Periscope repair
$225k part
$33M Savings
Liner bore seat damage in UH-60 helo gearbox $55k part
No Current Repair Available
Hydraulic lines and outer surfaces
B-1
~$100M annual DoD Savings
$15M Savings
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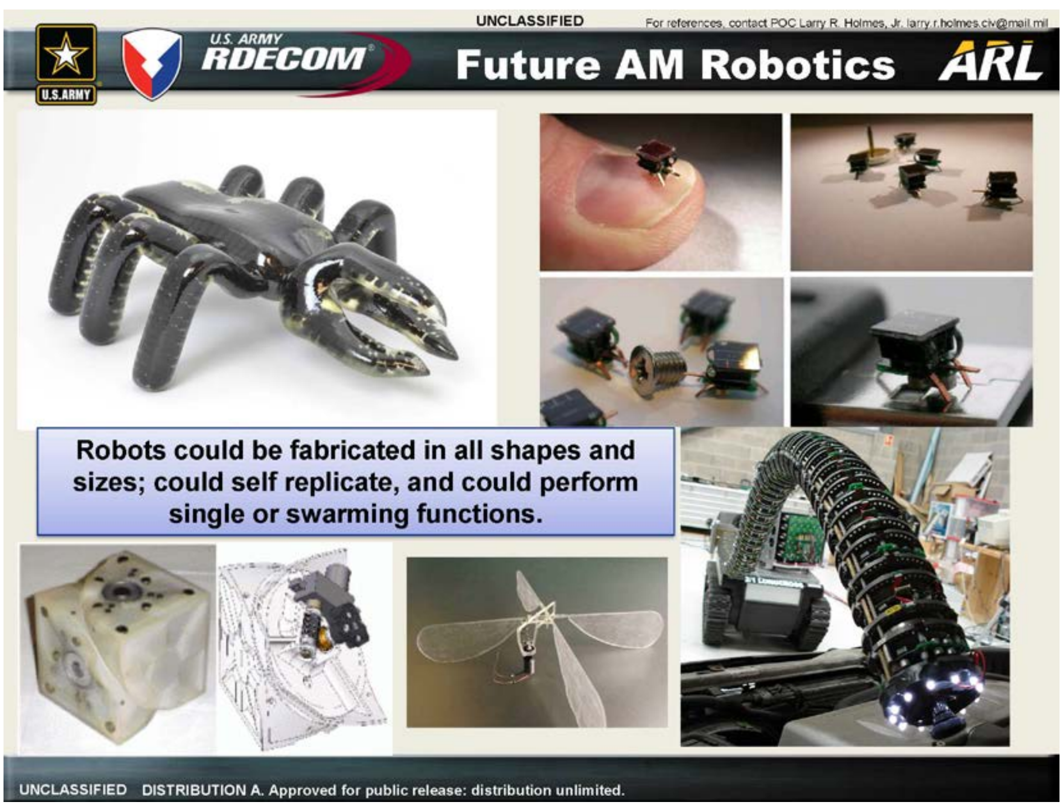
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Future AM Robotics
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Robots could be fabricated in all shapes and sizes; could self replicate, and could perform single or swarming functions.
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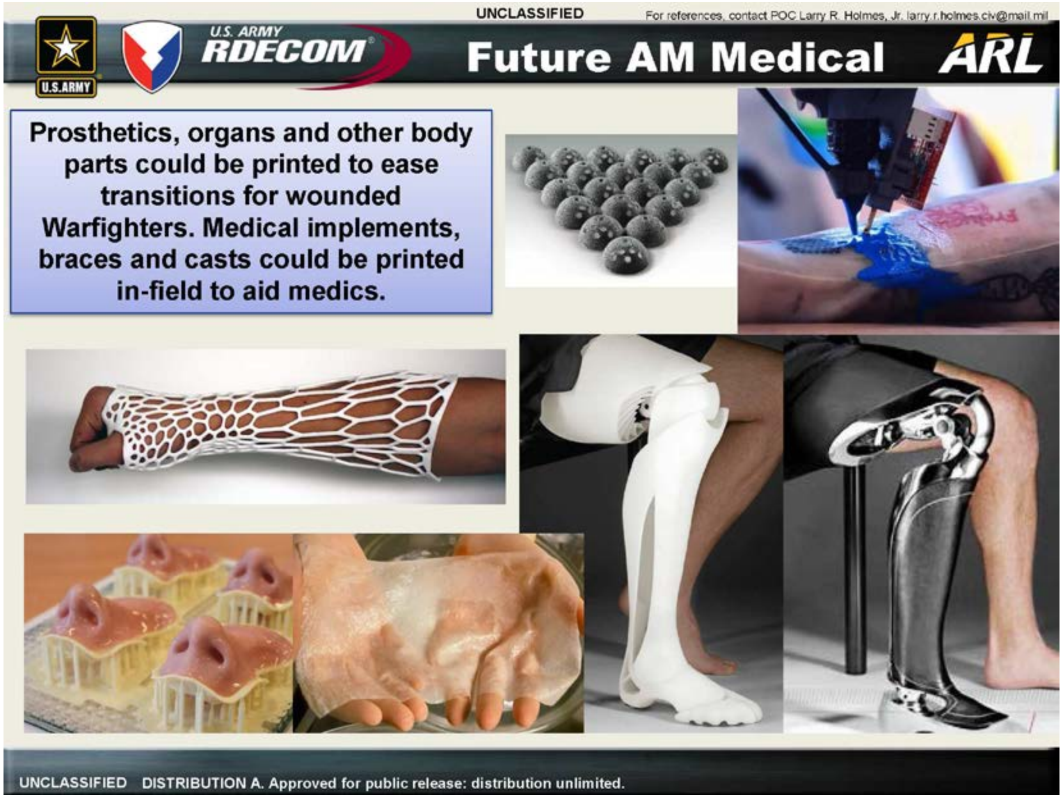

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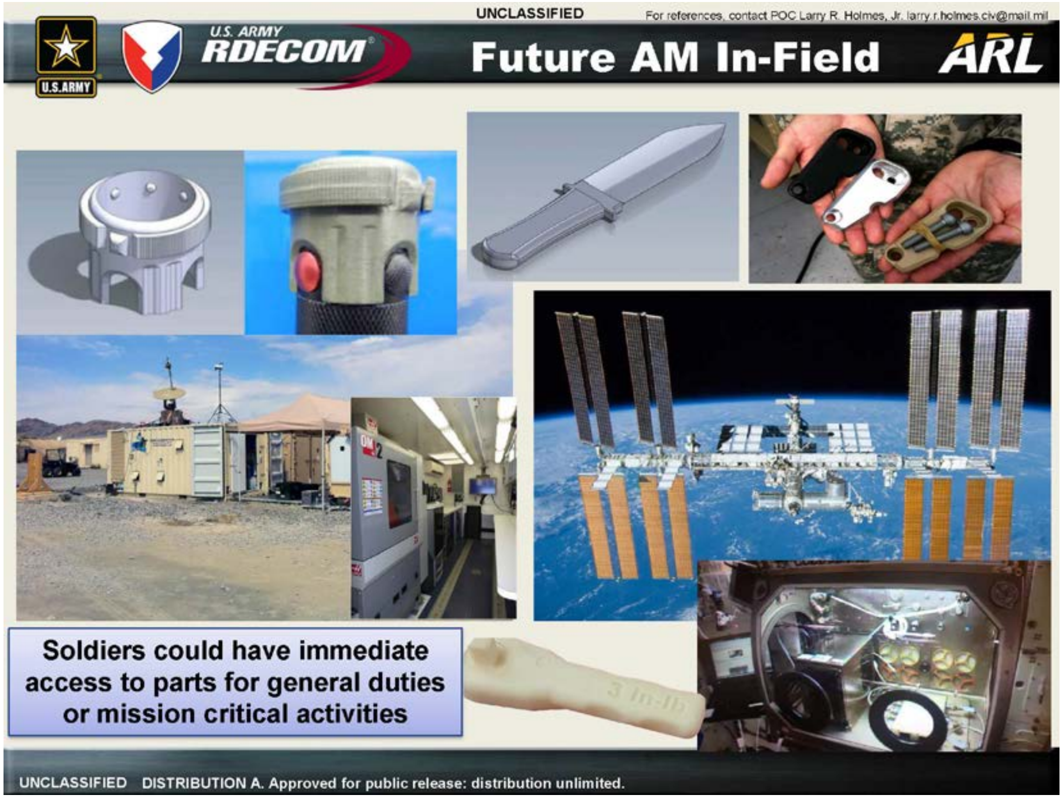

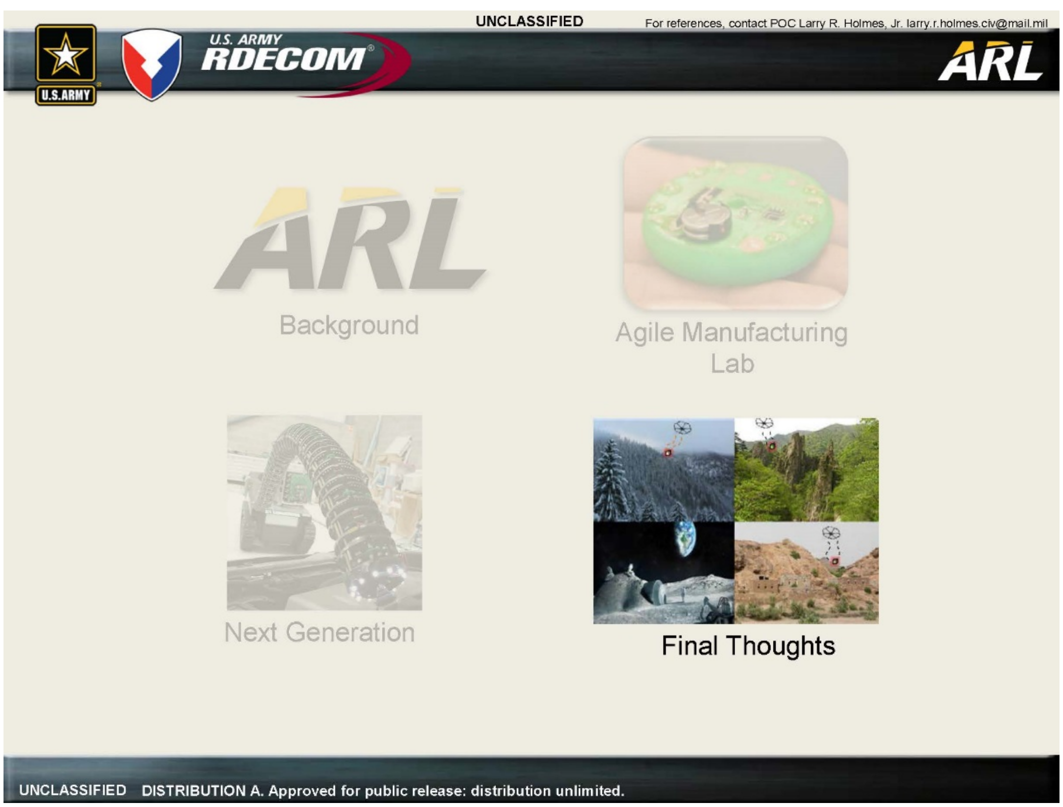

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Environment Driven
Single Machine
Multiplies
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The Forward Operations Reconnaissance and Terraforming (FORT) is a completely sustainable and autonomous system that is capable of manufacturing structures and devices that are customized to mission specific objectives and adapted to its local terrain. Suite of sensing, analyzing, and additive manufacturing technologies will enable the SAMS unit to relieve the logistical issues that arise in supporting unique missions in rugged terrain or dire scenarios.
Emerging Sciences
• Printing indigenous materials
• Compact additive systems
• Local environmental camouflage
Materials in Extreme Environments
• Printing immediate resources
• Characterization and modeling of surrounding resources for functionality
Extreme Energy Science
• Harvesting energy in any condition
• Reliable and robust energy storage that can sustain manufacturing
Hierarchical Computing
• Rigorous computational modeling of environment adapted structure and device design
• High speed database search and optimization for adaptive manufacturing
Network Sciences
• Robust geographical and climate database
• Connecting intelligent and autonomous manufacturing system
• Reliable, high speed communication network
Autonomous Systems Technology
• Adaptive customization of materials
• Intelligent on-the-fly design of structure and device functionality
Current Additive Manufacturing Research in Support of this Plan
• Materials development, including polymers, metals, ceramics, organics and biomimetics
• Technology development, including single system multi-material processing, and field aided structure tailoring
• Advancing the scientific areas of embedded sensing, communications and electronics
Environment Driven
Single Machine
Multiplies
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AM Research Road Map
ARL
Material and Technology Cert and Qual
Information Security
Technology Development
Materials Development
Generation After Next After Next
• Sikorsky, ARL, AMCOM and NAVAIR qualify cold spray for UH-60 Sump → TRL 9
Before
After
• Multi-Material & Self Healing
• Ballistic Surrogates
• Prosthetics, Implants and Surrogates
• Structural, Electronic, Network and Systems Engineering
NOW
• 3D Printed Auxetic Structures for acoustic energy manipulation
and on demand
• Print-to-Fit, printed armor
Next -Gen is In-Progress
• ARL Patent Awarded for E-field particle alignment in 3D printed polymer structures
• Air, Ground and Aquatic Autonomous Systems
• 3D Electronics and Antennas
• Microfluidics
• Structural Health Monitoring through integrated sensing
Future
• Large-Scale "print and drive"
2000 -
2015
2030
2045
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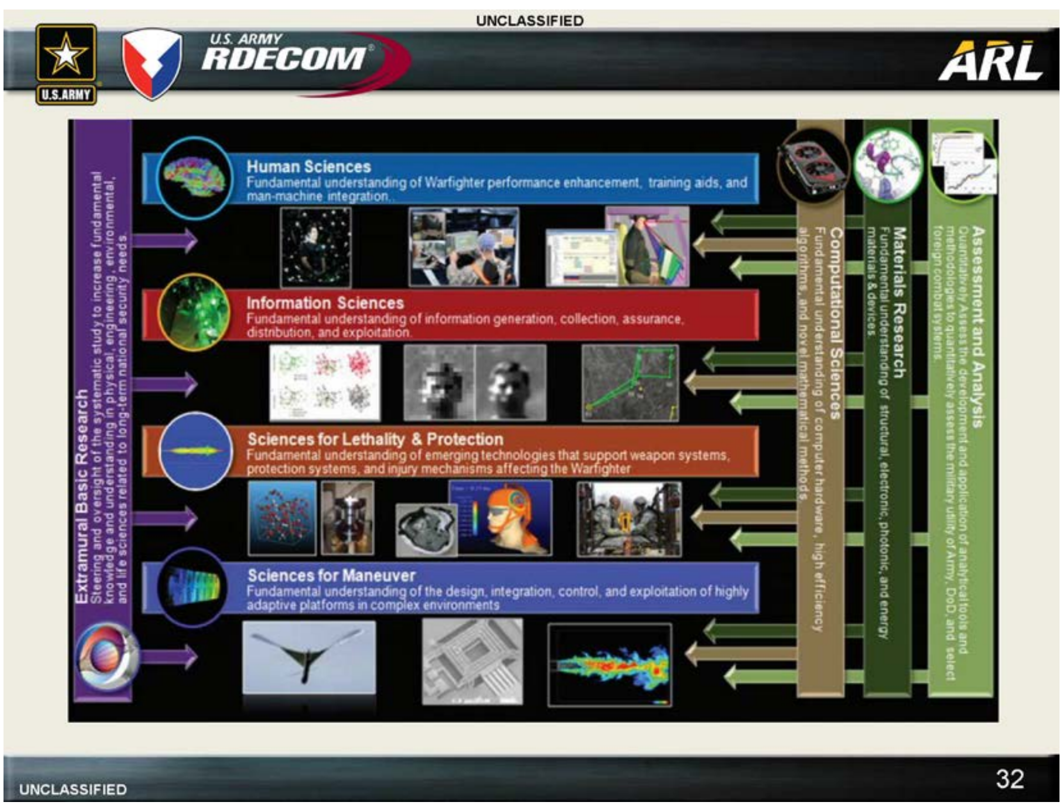

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Human Sciences
Fundamental understanding of Warfighter performance enhancement, training aids, and man-machine integration.
Information Sciences
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Sciences for Lethality & Protection
Fundamental understanding of emerging technologies that support weapon systems, protection systems, and injury mechanisms affecting the Warfighter
Sciences for Maneuver
Fundamental understanding of the design, integration, control, and exploitation of highly adaptive platforms in complex environments
Extramural Basic Research
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Materials Research
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Assessment and Analysis
Quantitatively Assess the development and application of analytical tools and methodologies to quantitatively assess the military utility of Army, DoD, and select foreign combat systems.
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List of Symbols, Abbreviations, and Acronyms

3-D	3-dimensional
AFRL	Air Force Research Laboratory
AM	additive manufacturing
ARL	Army Research Laboratory
CT	computed tomography
MFPT	Machinery Failure Prevention Technology

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